CPT data, Soil Behavior Type (SBT) and interpretation of geostratigraphy

The ideal site investigation procedure

1. Determine the geologic setting from sources such as geologic maps, i.e. what are the geologic formations expected at the project site.

2. Determine the soil and groundwater conditions expected at the project site from pre-existing boreholes, soundings, water wells, pile driving records, etc..

3. Perform CPTs to develop a stratigraphic model and identify geotechnically significant soils.

4. Perform CPTs adjacent to step 3 CPTs, to perform pore pressure dissipation tests at identified appropriate soil strata.

5. Drill and sample at locations and depths identified as being critical to the design, construction and performance of the project.

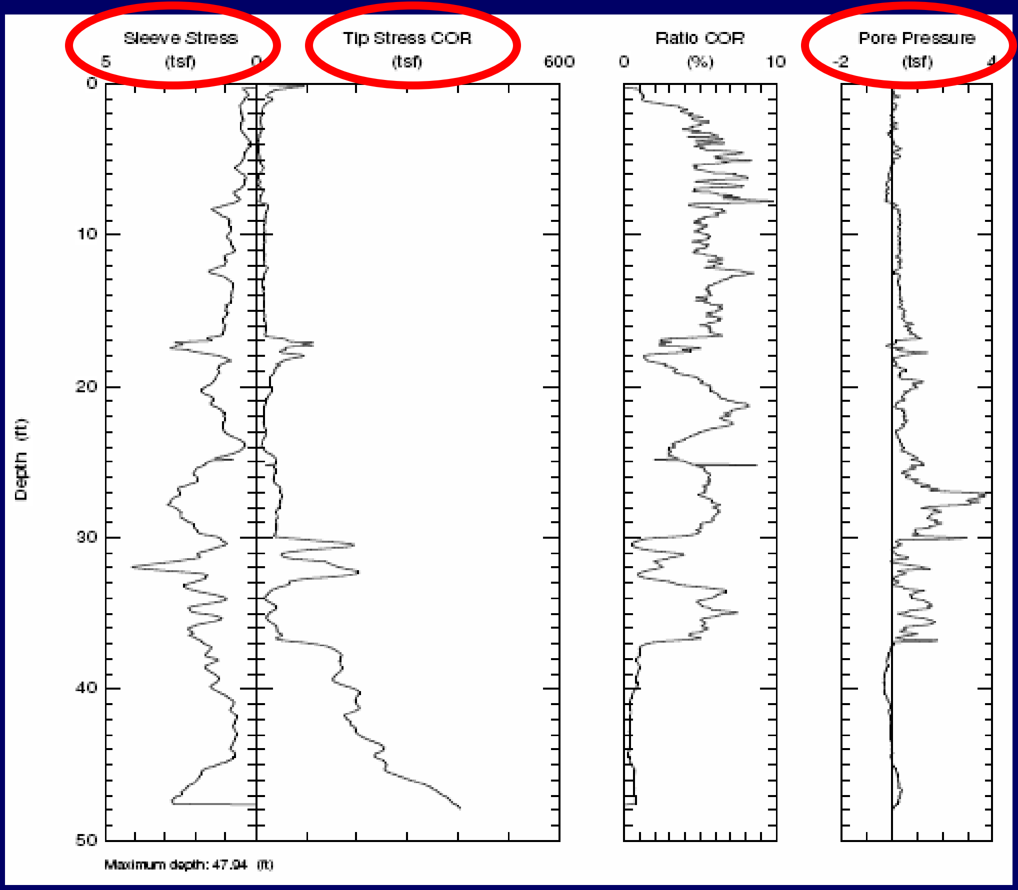
Topics

- Values measured by the CPT
- Correcting CPT data for the effects of penetration pore pressures
- Soil Behavior Type determination
- Data processing with the Vertek CPT
- Interpretation of the CPT geostratigraphy

Values measured by the CPT

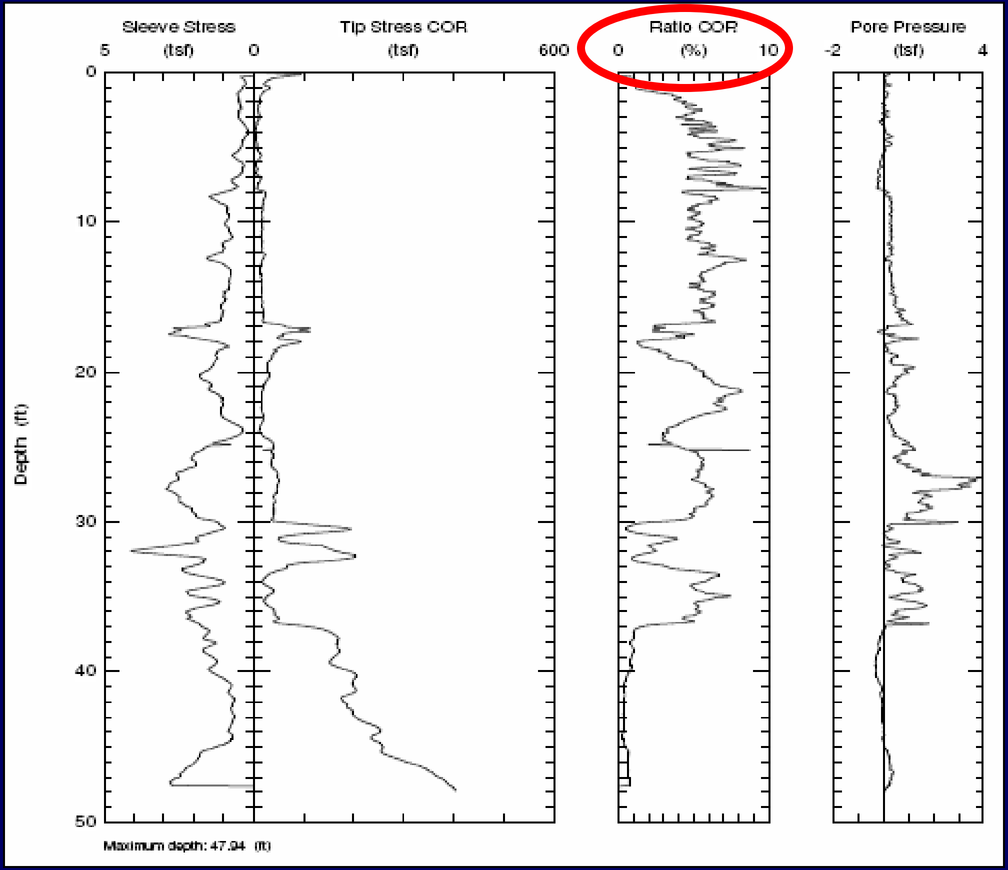
Values <u>measured</u> by the Cone Penetration Test

- tip stress: q_c (TSF or psi)
- sleeve stress: f_s (TSF or psi)
- pore pressure: u_t (TSF or psi)



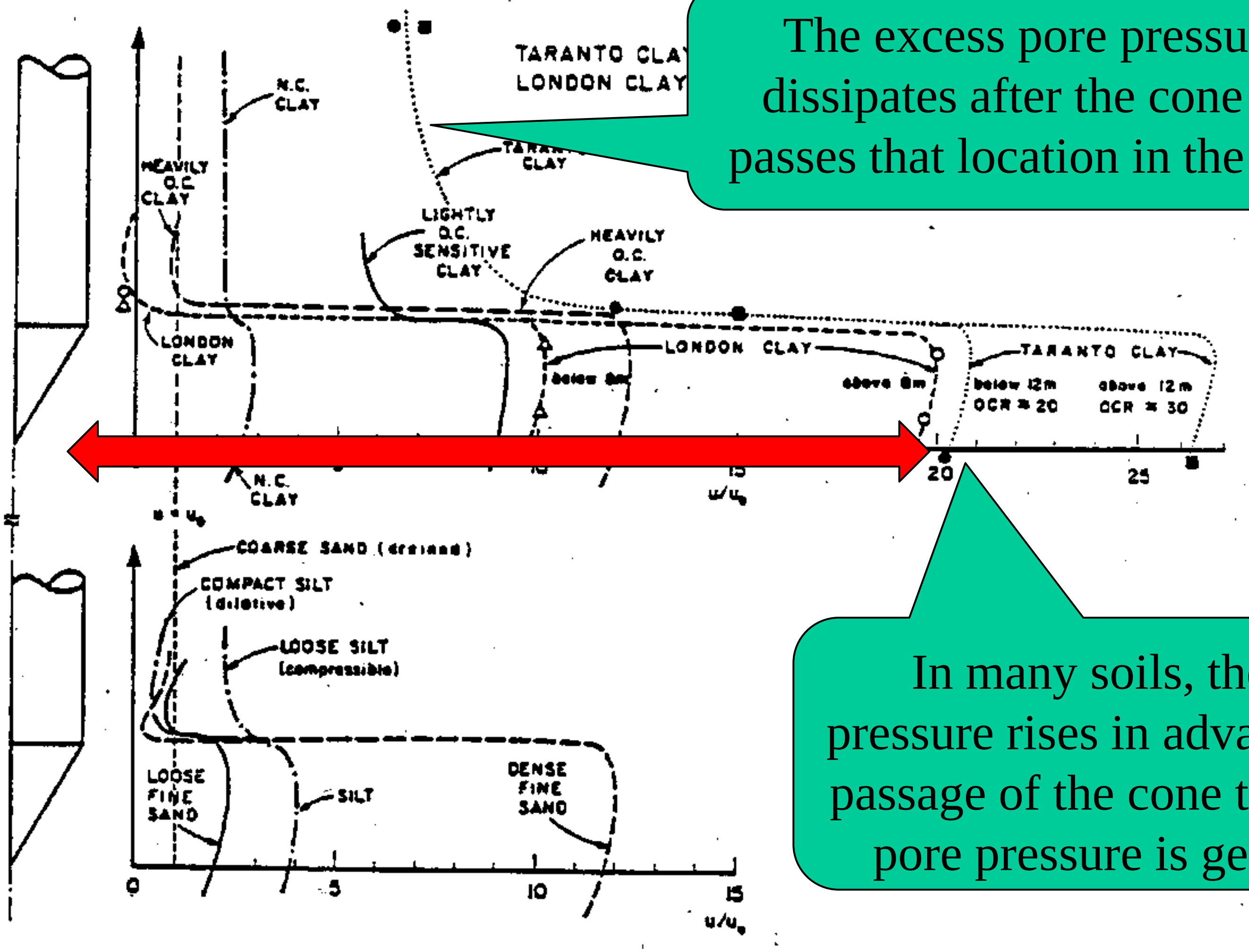
An essential parameter calculated from CPT data: friction ratio

- ratio or friction ratio: $R_f = f_s/q_c \times 100\%$
- R_f is a dimensionless value.



Pore pressure terminology

$u_t = u = u_2$	measured penetration pore pressure at a specific depth
u_o	measured static pore pressure or equilibrium pore pressure at a specific depth
$\Delta u = u_t - u_o$	calculated excess pore pressure generated by the penetrating cone penetrometer tip

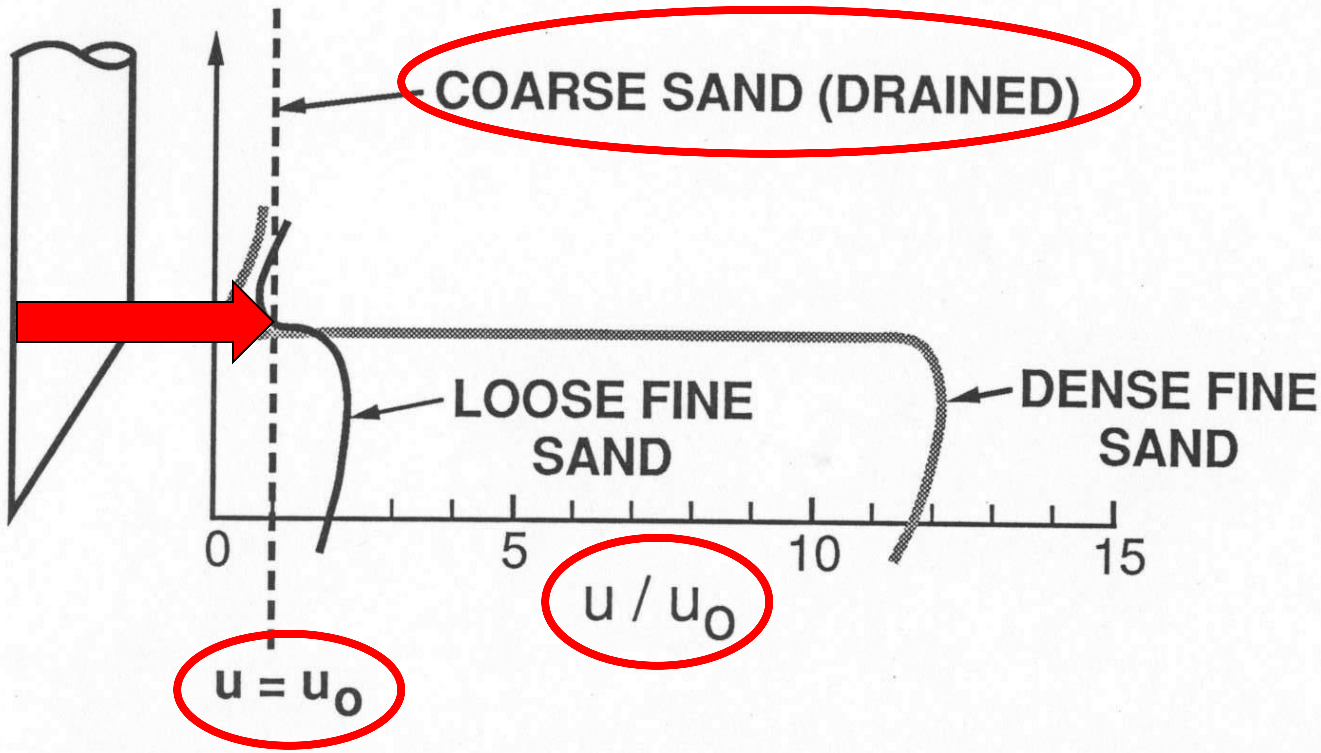


The excess pore pressure dissipates after the cone tip passes that location in the soil.

In many soils, the pore pressure rises in advance of the passage of the cone tip. Excess pore pressure is generated.

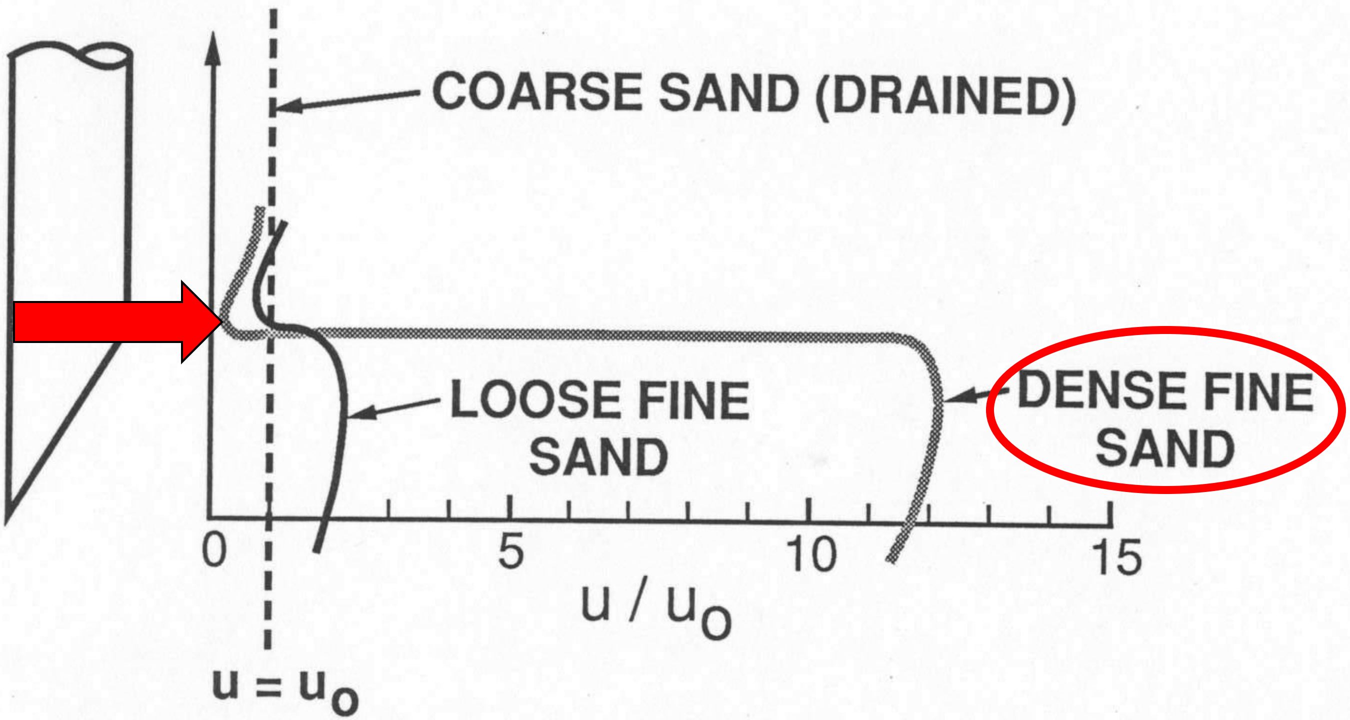
The magnitude and distribution of pore pressures adjacent to the cone tip during penetration

Pore pressures adjacent to the passing penetrometer in well drained coarse sand remain at static pore pressure levels



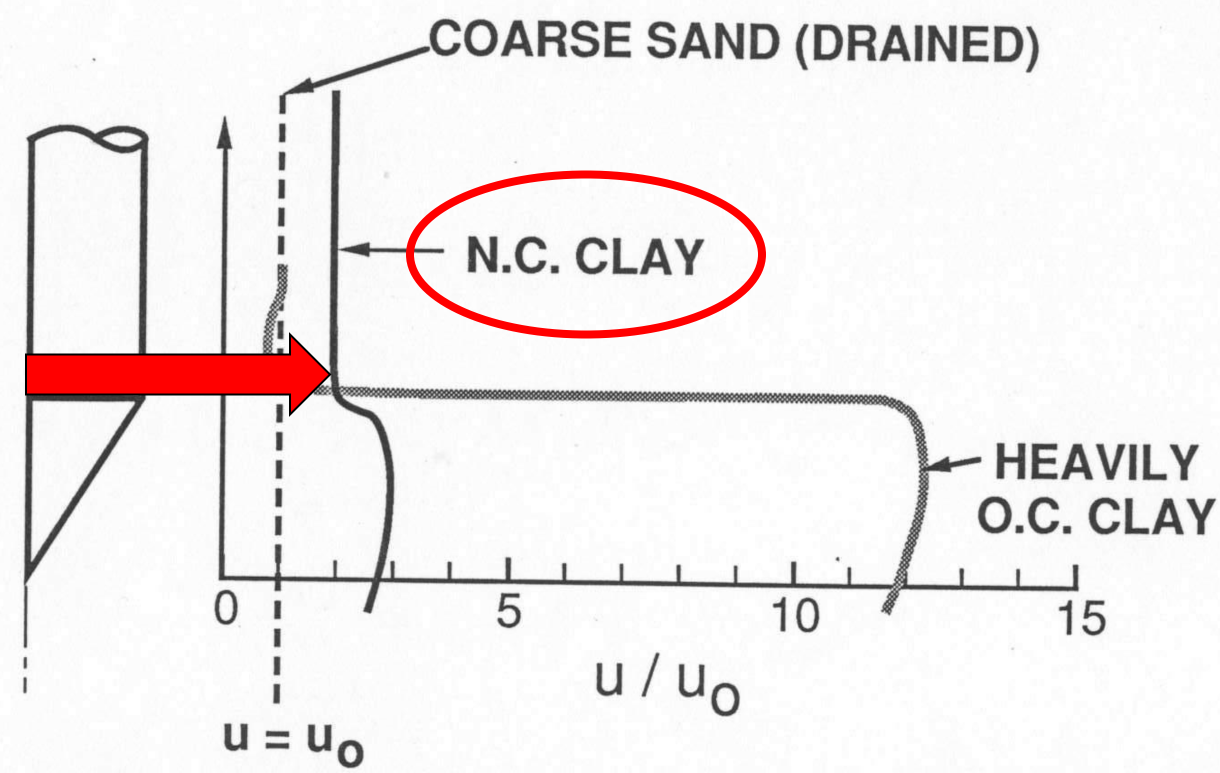
PORE PRESSURE DISTRIBUTION DURING CPT IN SANDS

Pore pressures less than the static value are generated in dense fine sands at the point of pore pressure measurement



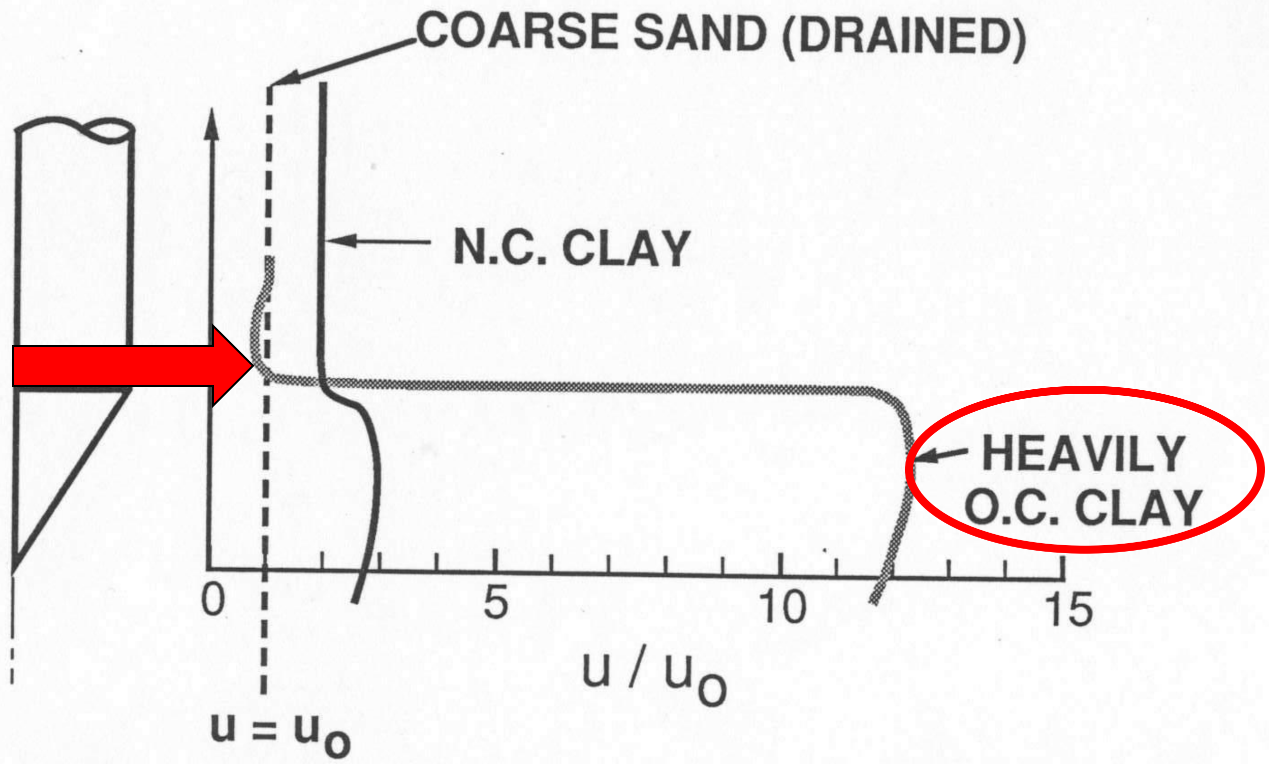
PORE PRESSURE DISTRIBUTION DURING CPT IN SANDS

Pore pressures in excess of the static value are generated in normally consolidated clays at the point of pore pressure measurement



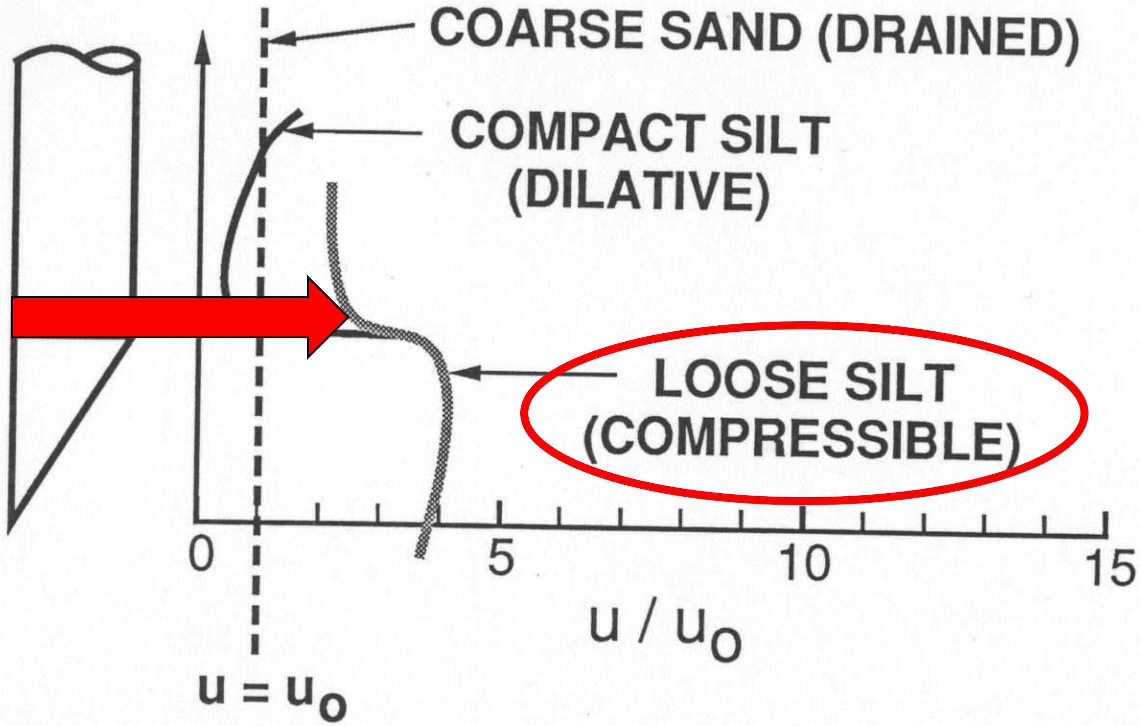
PORE PRESSURE DISTRIBUTION DURING CPT IN CLAYS

Pore pressures less than the static value are generated in over consolidated clays at the point of pore pressure measurement



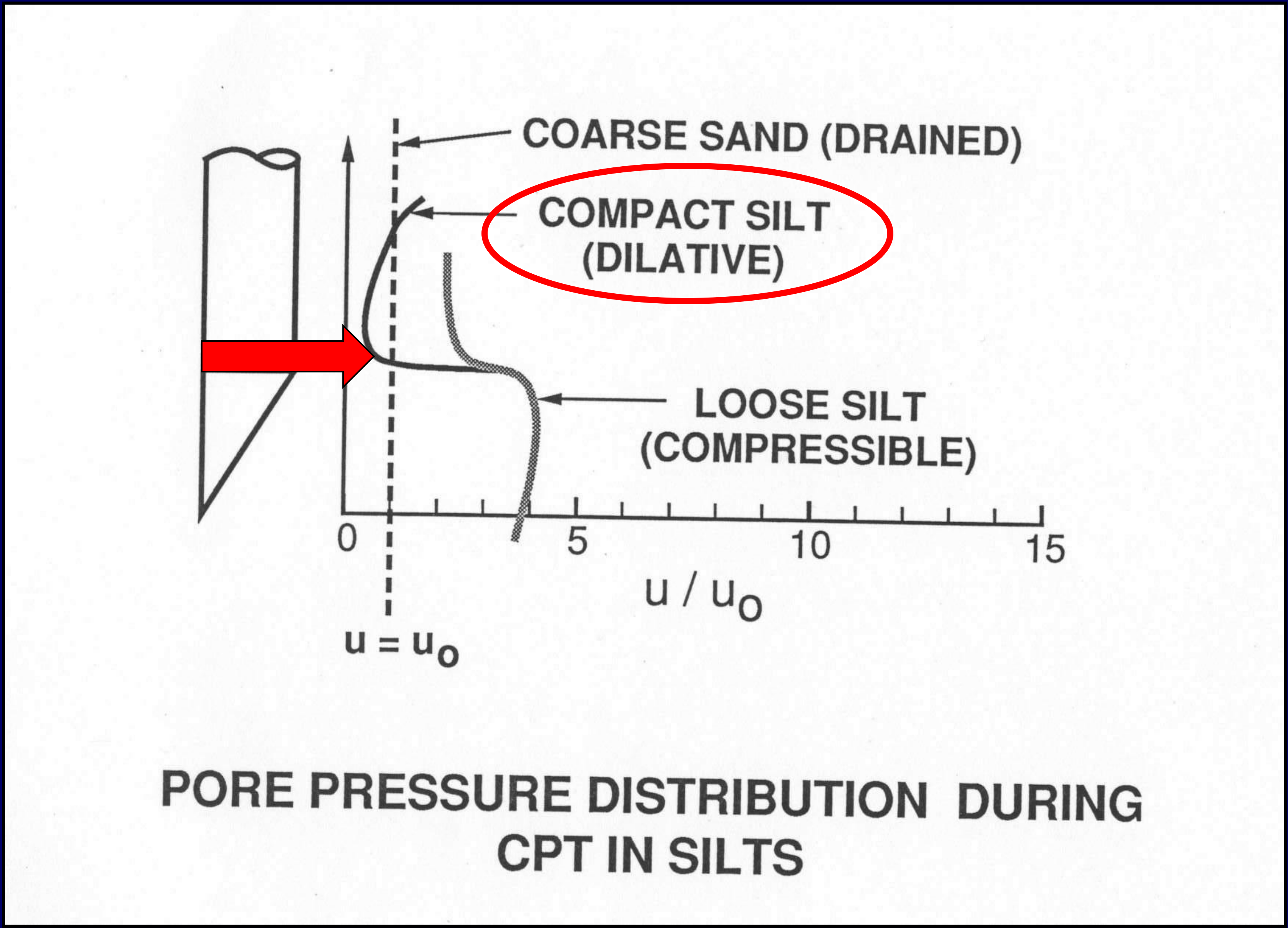
PORE PRESSURE DISTRIBUTION DURING CPT IN CLAYS

Pore pressures in excess of the static value are generated in loose silts at the point of pore pressure measurement



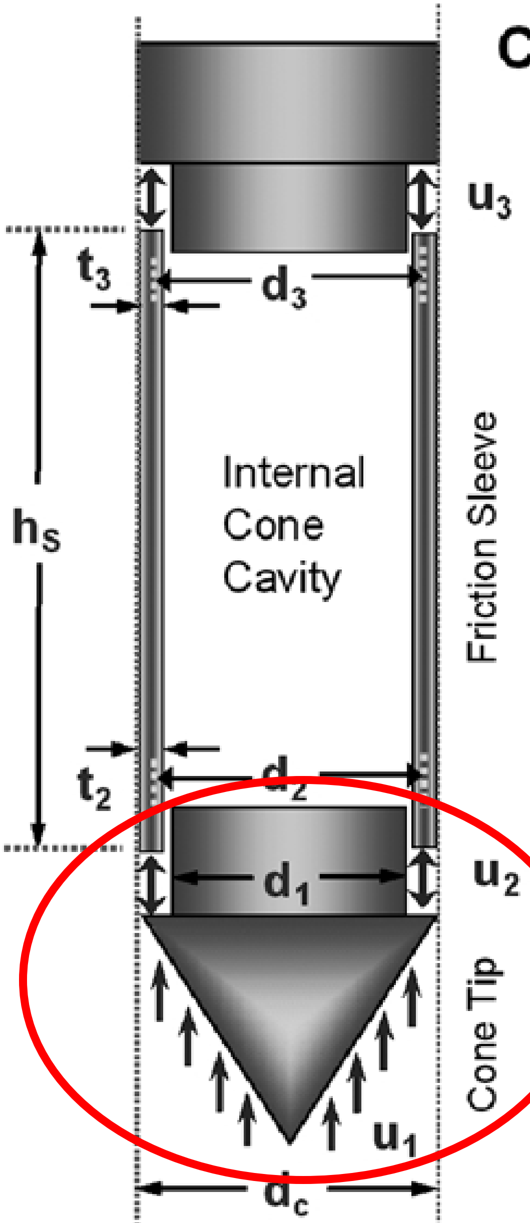
PORE PRESSURE DISTRIBUTION DURING CPT IN SILTS

Pore pressures less than the static value are generated in compact silts at the point of pore pressure measurement



Correcting CPT data for the effects of penetration pore pressures

Correction of cone tip data for penetration pore pressure



Corrections for Tip and Sleeve Readings

d_i = diameter geometry (as shown)
t_i = thickness of friction sleeve
u_i = measured porewater pressure
q_c = measured cone tip resistance
f_s = measured sleeve friction
q_t = total cone tip resistance
f_t = total sleeve resistance
a_n = tip net area ratio from triaxial test
b_n = sleeve net ratio from triaxial test
h_s = height of sleeve

Sleeve Friction:

$$f_t = f_s - (\pi d_2 t_2 u_2 + \pi d_3 t_3 u_3)/(\pi d_c h_s)$$

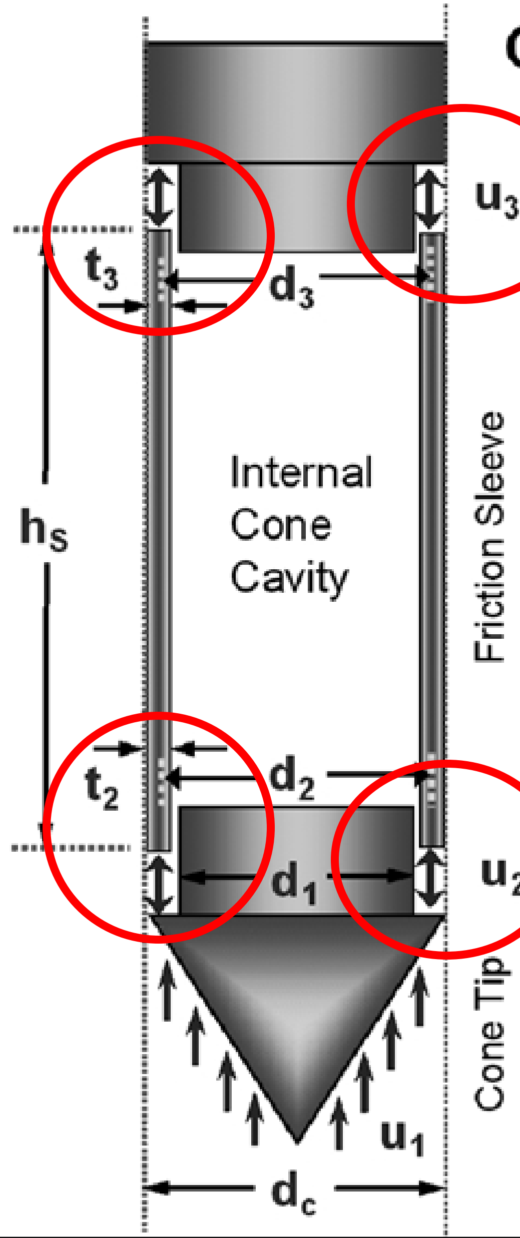
$$f_t \approx f_s - b_n u_2$$

Tip Resistance:

$$q_t = q_c + (1-a_n)u_2$$

Correction of sleeve friction data for penetration pore pressure

Corrections for Tip and Sleeve Readings



d_j = diameter geometry (as shown)
t_j = thickness of friction sleeve
u_i = measured porewater pressure
q_c = measured cone tip resistance
f_s = measured sleeve friction
q_t = total cone tip resistance
f_t = total sleeve resistance
a_n = tip net area ratio from triaxial test
b_n = sleeve net ratio from triaxial test
h_s = height of sleeve

Sleeve Friction:

$$f_t = f_s - (\pi d_2 t_2 u_2 + \pi d_3 t_3 u_3)/(\pi d_c h_s)$$

$$f_t \approx f_s - b_n u_2$$

Tip Resistance:

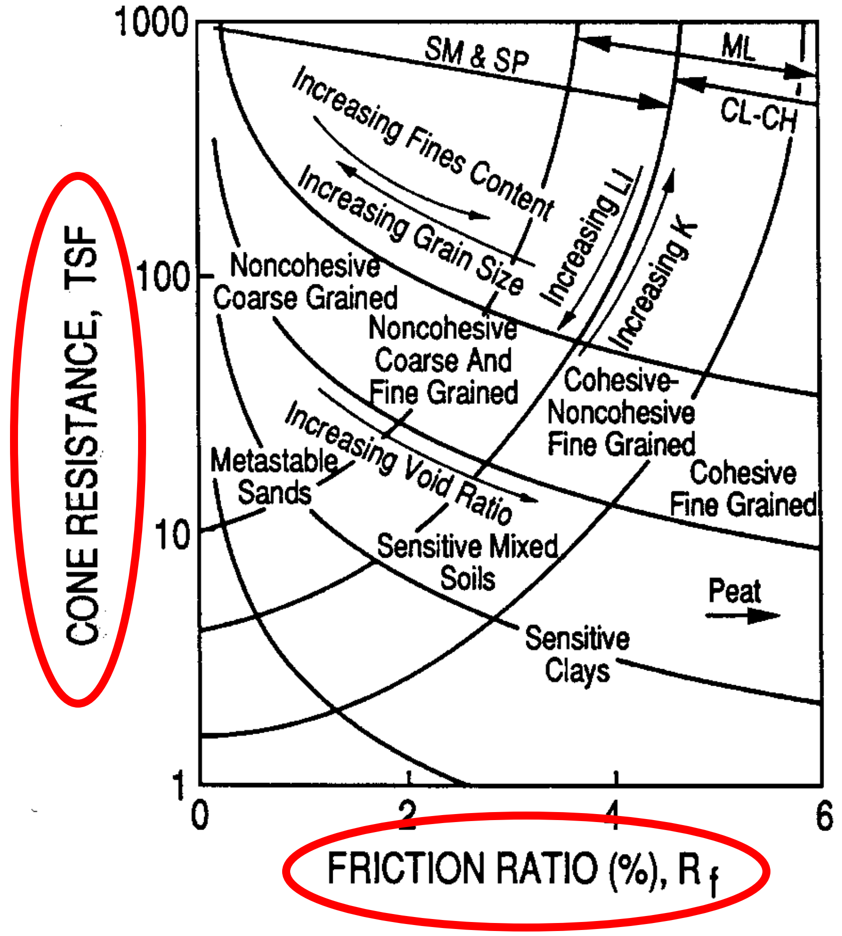
$$q_t = q_c + (1-a_n)u_2$$

Soil Behavior Type determination

Soil Behavior Type (SBT) classification schemes

- Douglas and Olsen (1981)
- Robertson and Campanella (1983)
- Robertson (1985)
- Robertson (1990)
- Jefferies and Davies (1993)

Soil classification (Douglas and Olsen, 1981)



SOIL CLASSIFICATION CHART FOR
STANDARD ELECTRONIC FRICTION CONE

Simplified CPT soil type classification (Robertson and Campanella, 1983)

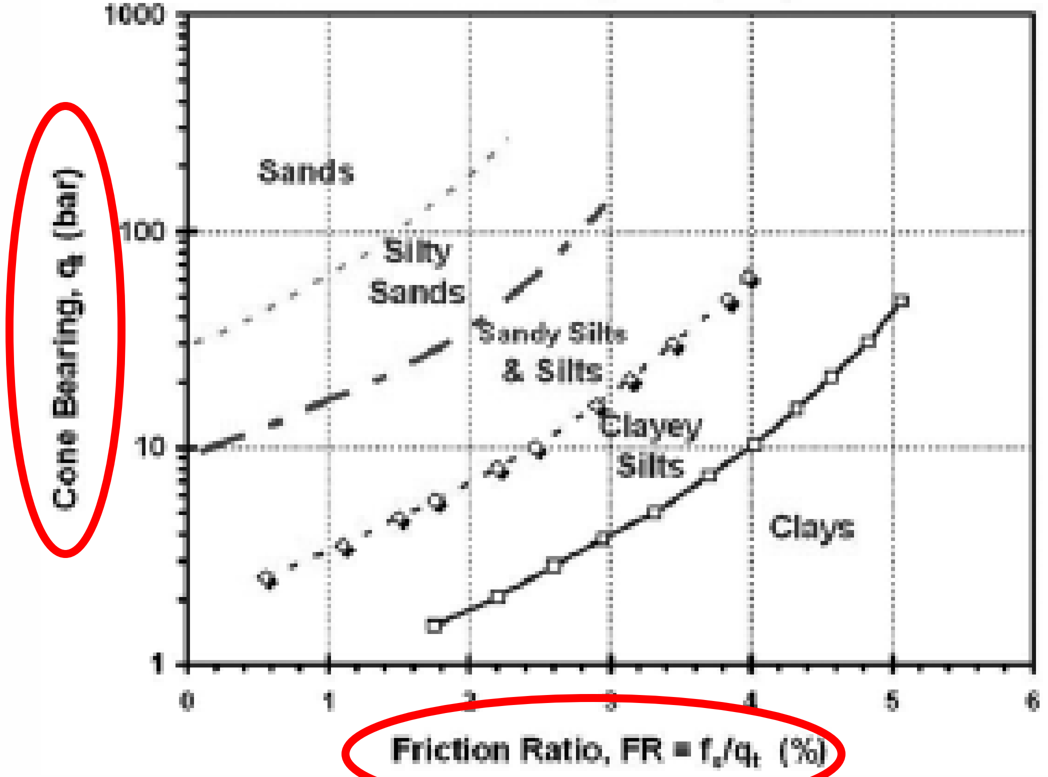
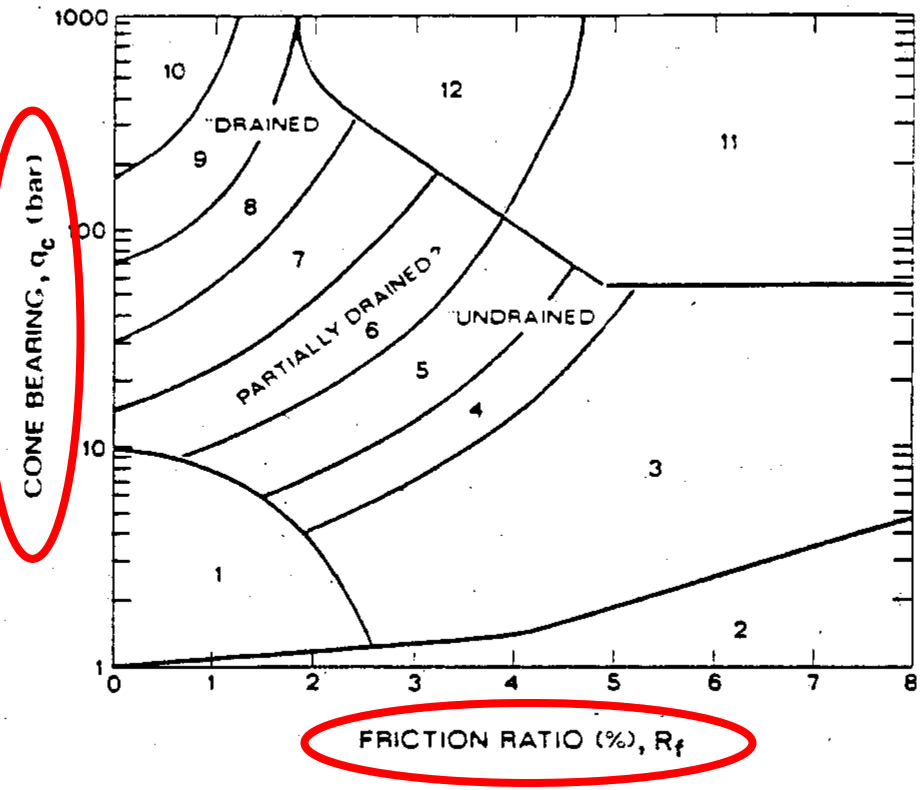


FIGURE 24 Simplified CPT soil type classification chart (after Robertson and Campanella 1983).

Simplified Soil Classification Chart (Robertson, 1985)



Zone	q_c/N	Soil Behaviour Type
1)	2	sensitive fine grained
2)	1	organic material
3)	1	clay
4)	1.5	silty clay to clay
5)	2	clayey silt to silty clay
6)	2.5	sandy silt to clayey silt
7)	3	silty sand to sandy silt
8)	4	sand to silty sand
9)	5	sand
10)	6	gravelly sand to sand
11)	1	very stiff fine grained (*)
12)	2	sand to clayey sand (*)

(*) overconsolidated or cemented

Figure 4.2 Simplified Soil Classification Chart for Standard Electronic Friction Cone (Robertson, 1985)

Normalized Soil Behavior Type Classification (Robertson 1990)

<u>Normalized cone tip resistance</u>

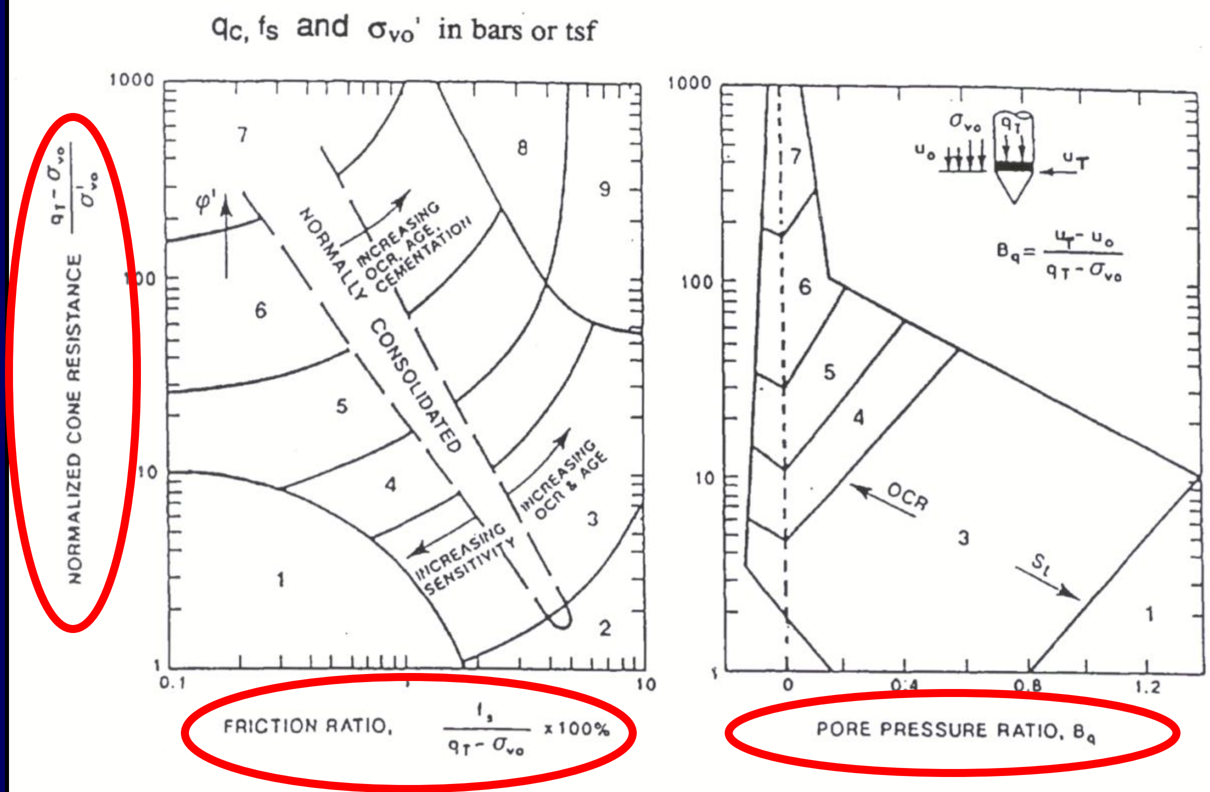
$Q = (q_t - \sigma_{v0})/\sigma_{v0}'$

<u>Normalized Friction Ratio</u>

$F = f_s/(q_t - \sigma_{v0})$

<u>Normalized Pore Pressure Ratio</u>

$B_q = (u_t - u_0)/(q_t - \sigma_{v0})$



1. Sensitive fine grained
2. Organic soils - peats
3. Clays - clay to silty clay
4. Silt mixtures - clayey silt to silty clay
5. Sand mixtures - silty sand Sandy silt
6. Sands - clean sand to silty sand
7. Gravelly sand to sand
8. Very stiff sand to clayey sand (heavily overconsolidated or cemented)
9. Very stiff fine grained (heavily overconsolidated or cemented)

FIG. 6.8. Soil Behavior Type Classification Charts for CPT (after Robertson, 1990)

Extended Soil Classification Chart (Jefferies and Davies, 1993)

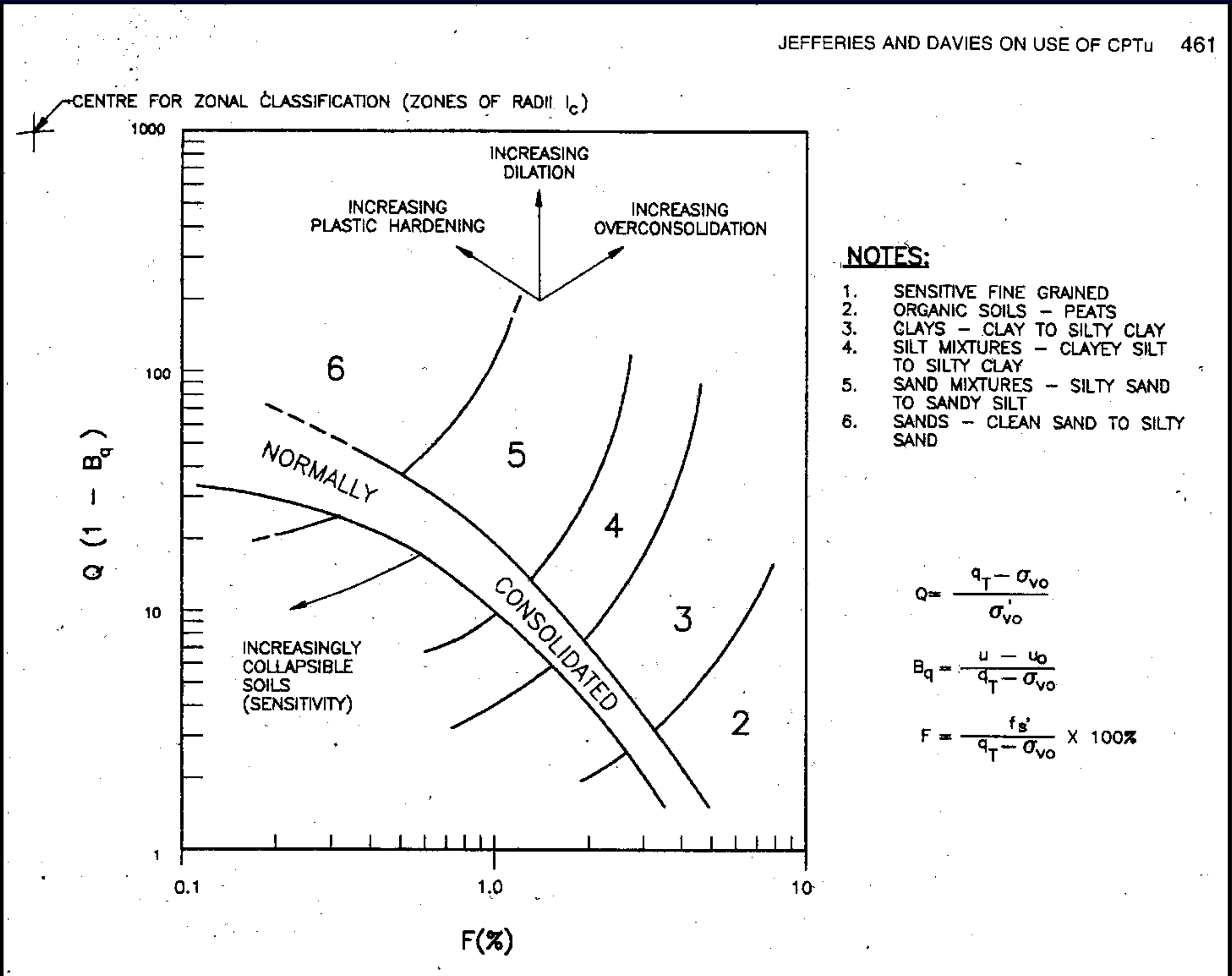


FIG. 3—*Extended soil classification chart for piezometric CPTu data (after Jefferies and Davies, 1991).*

$I_c = ((3 - \log(Q_t(1 - B_q)))^2 + (1.5 + 1.3(\log F_r))^2)^{0.5}$ (Jefferies and Davies, 1993)

$I_c = ((3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2)^{0.5}$ (Robertson, 1997)

Exercise 1

Determine the Soil Behavior Type
from cone penetrometer data

Recommendations for selecting a soil behavior type classification scheme

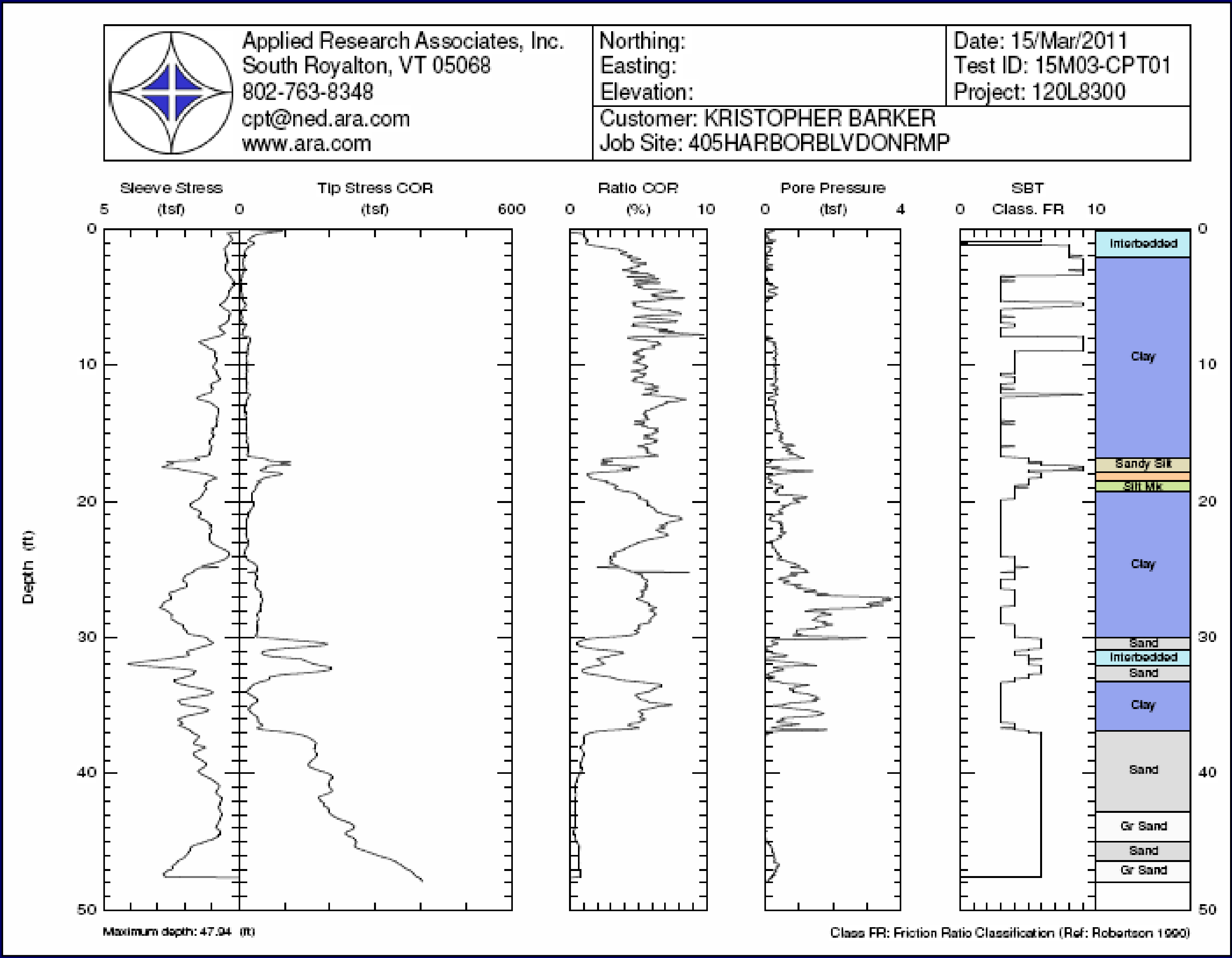
* It is acceptable to use the simplified soil classification chart when sounding depths are less than 100 feet, but there may be errors for soft, low OCR fine grained soils.
* It is acceptable to use the simplified soil classification chart with pore pressure corrections (q_t in place of q_c) when the sounding depth is less than 100 feet to improve the characterization of soft low OCR fine grained soils.
* However, when pore pressure data is available or when the sounding depth is greater than 100 feet, it is recommended that you use the Normalized SBT Classification Chart (Robertson, 1990).

Data processing with the Vertek CPT

Vertek data processing software

1. Pro Dat: Processes the digital cone data into pressures, and creates
    1. an Excel compatible (.csv) tabular data file
    2. a notepad compatible (.stg) tabular data file
    3. a gINT compatible (.gin) graphical file
    4. a pdf of the graphical representation of the post-processed data
    5. a data file that is the input (.ecp) for the CPT Graph program
2. CPT Graph: Creates a graphical output of the measured cone penetrometer data, as well as calculating corrected and normalized cone data values
3. Diss Graph: Creates a measured total pore pressure - time graph from the ____D.depth data file
4. Seis Graph: Creates a seismic signal – time graph from the ____S.depth data file

Graph produced using the program Pro Dat

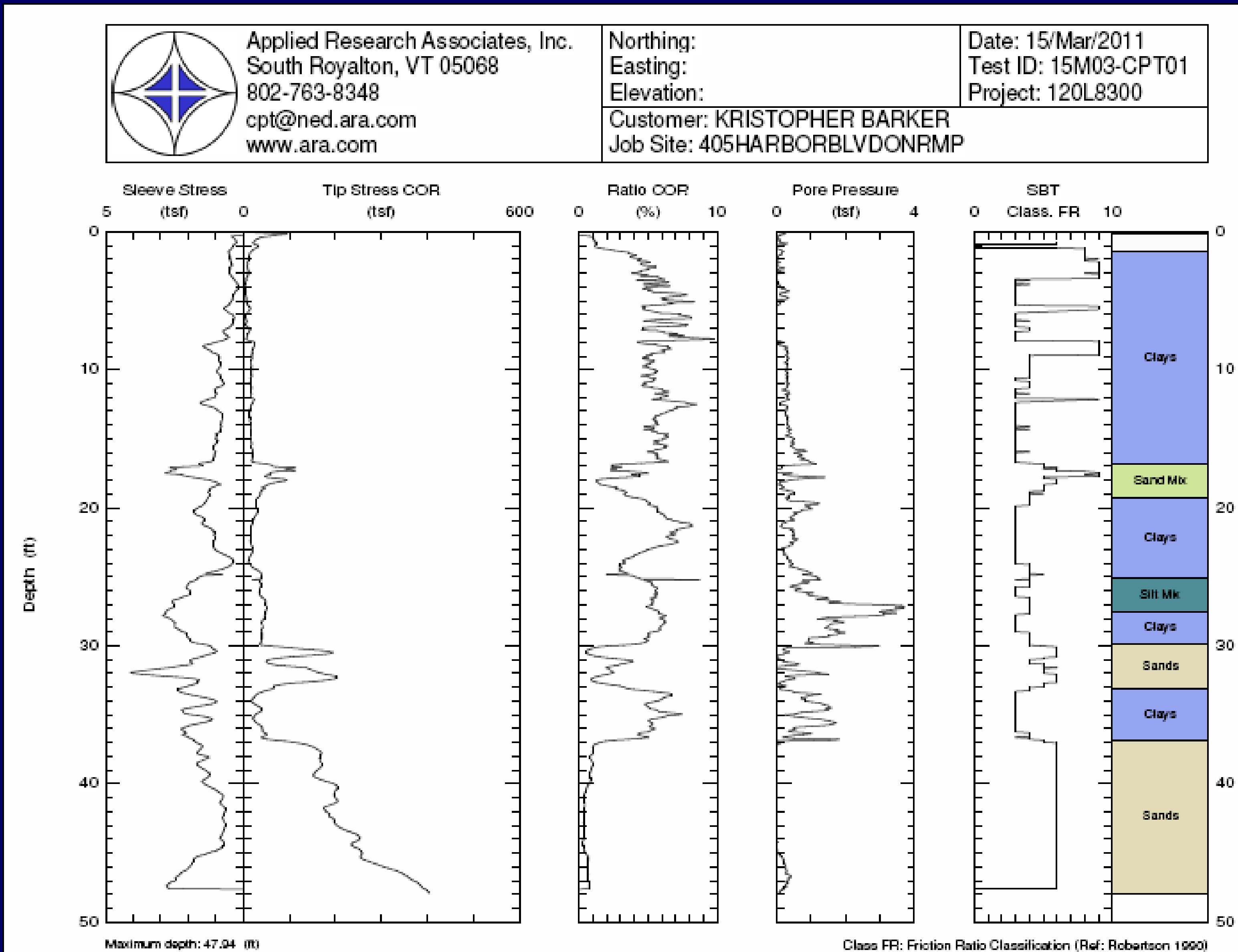


Tabular data file produced using the program Pro Dat

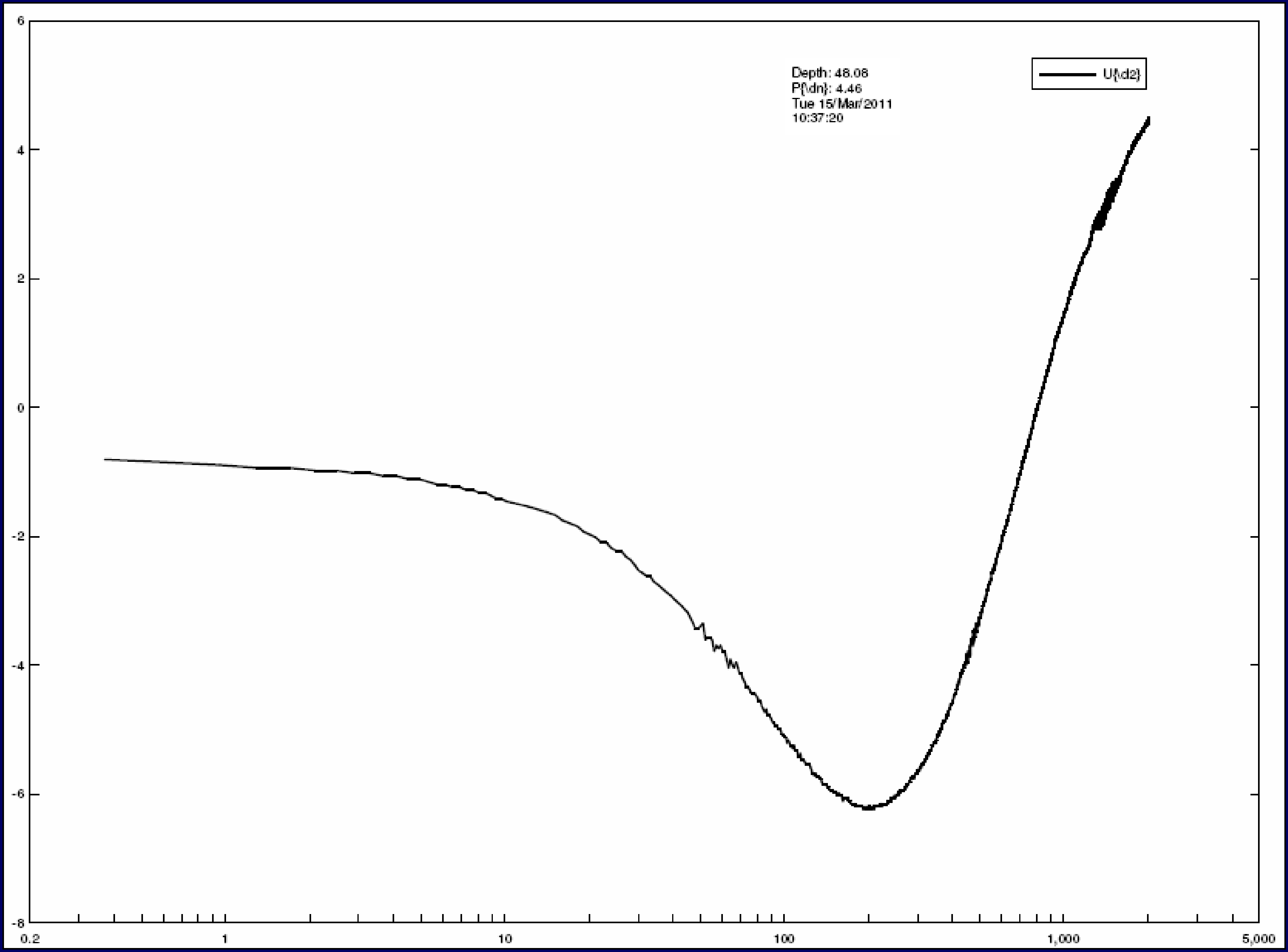
Software: Cone_TAP v 3.02
Client: KRISTOPHER BARKER
Date: 15-Mar-11
Test Id: 15M03-CPT01
Project: 120L8300
Site: 405HARBORBLVDONRMP
Location: 12-ORA-405-11.51
Cone Id: 2579.118XX
GWT (ft):
Soil Density (pcf):
Surface Elev:
Northing:
Easting:

Depth (ft)	Sleeve Stress (tsf)	Tip Stress UNC (tsf)	Tip Stress COR (tsf)	Ratio COR (%)	Pore Pressure (tsf)	Inclination X (deg)	Inclination Y (deg)	Excitation (Vdc)	Overburden (tsf)	Eff. Overburden (tsf)	Wet Density (pcf)	Class. FR (Rob. 1990)	Class. PP (Rob. 1990)
0	0	0	0	0	0	0	0	1	0.00E+00	0.00E+00	120	-99	-99
0.18014	0	94.9	95	0	0.25	3.97	-1.44	1	1.08E-02	5.19E-03	120	-99	-99
0.25088	0	70.1	70.1	0	0.11	-3.66	2.23	1.001	1.51E-02	7.23E-03	120	-99	-99
0.3304	0.43	57.9	57.9	0.74	0.04	-1.19	0.56	1.001	1.98E-02	9.52E-03	120	-99	-99
0.40905	0.4	38.4	38.4	1.05	0.01	0.1	1.25	1.001	2.45E-02	1.18E-02	120	-99	-99
0.47407	0.35	33.9	34	1.04	0.07	-0.02	0.03	1.001	2.84E-02	1.37E-02	120	-99	-99
0.53559	0.32	30	30	1.08	0.09	-0.64	0.4	1.001	3.21E-02	1.54E-02	120	-99	-99
0.59622	0.29	27.1	27.1	1.06	0.01	-0.28	0.87	1	3.58E-02	1.72E-02	120	-99	-99
0.65817	0.28	24.8	24.8	1.11	0.1	-0.04	1.08	1	3.95E-02	1.90E-02	120	-99	-99
0.72056	0.27	22.7	22.7	1.2	0.08	0.52	1.04	0.999	4.32E-02	2.08E-02	120	-99	-99
0.78602	0.24	20.6	20.6	1.18	0.12	-0.58	0.73	0.999	4.72E-02	2.26E-02	120	6	7
0.85281	0.28	21.8	21.9	1.28	0.31	0.04	0.39	1	5.12E-02	2.46E-02	120	6	7
0.91915	0.32	24.8	24.8	1.28	0.22	-0.33	0.35	1	5.52E-02	2.65E-02	120	6	7
0.98286	0.36	30.8	30.8	1.16	0.02	0.2	0.76	1	5.90E-02	2.83E-02	120	-99	-99
1.05008	0.39	33	33	1.18	0.05	0.04	0.79	1	6.30E-02	3.02E-02	120	-99	-99
1.11467	0.39	33	33	1.19	0	-0.2	0.87	1.001	6.69E-02	3.21E-02	120	-99	-99
1.18101	0.41	27.7	27.7	1.46	0.01	0.13	0.66	1.001	7.09E-02	3.40E-02	120	6	7
1.24736	0.44	24.7	24.7	1.76	0.02	-0.18	0.73	1	7.48E-02	3.59E-02	120	8	7
1.31282	0.47	20.2	20.3	2.3	0.12	-0.03	0.71	1.001	7.88E-02	3.78E-02	120	8	7
1.37829	0.51	19.9	19.9	2.55	0.15	0.05	0.54	1	8.27E-02	3.97E-02	120	8	7
1.44287	0.53	17.2	17.2	3.08	0.2	-0.07	0.51	1	8.66E-02	4.16E-02	120	8	7

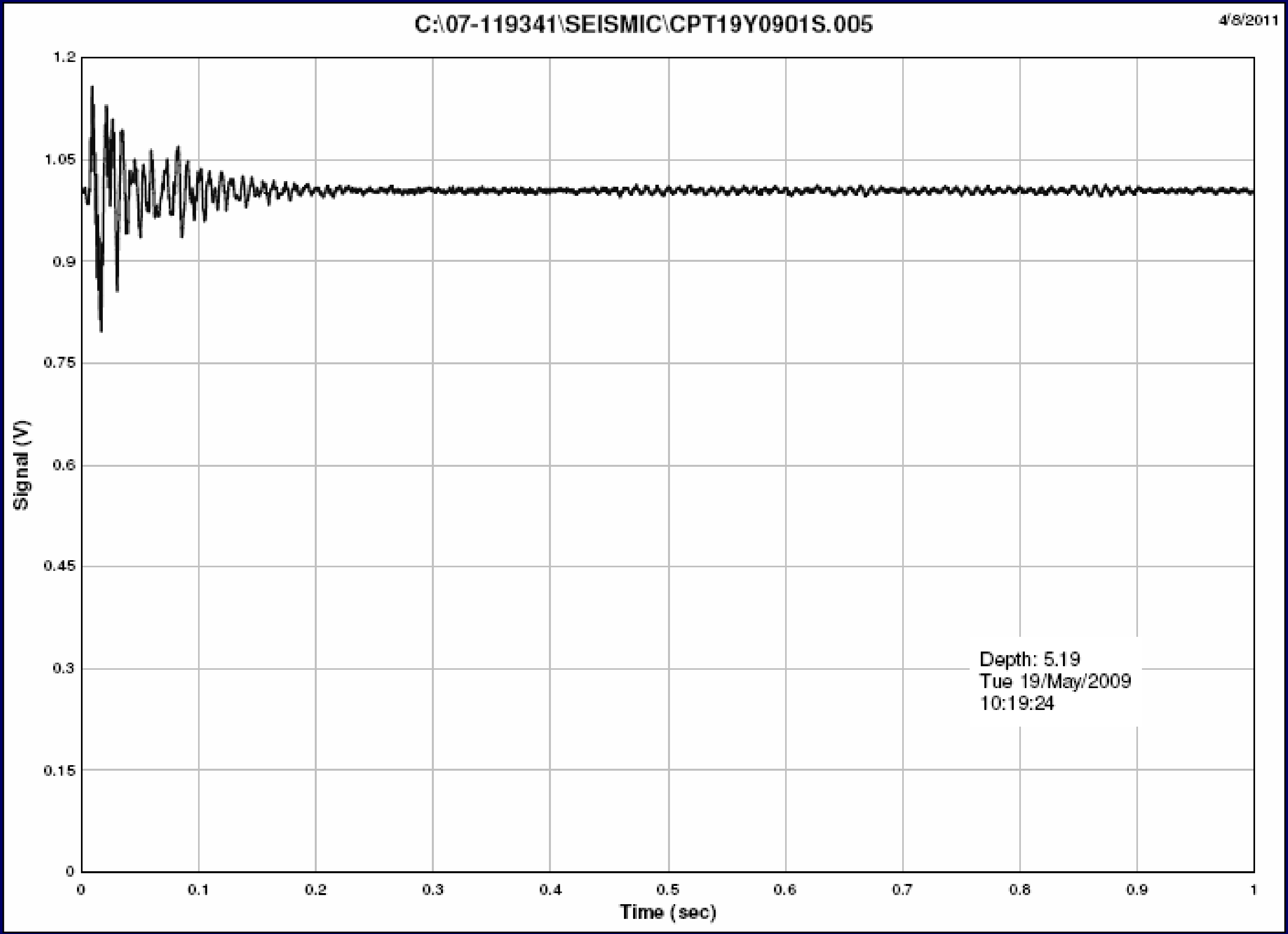
Graph produced using the program CPT Graph



Graph produced using the program Diss Graph (pore pressure dissipation curve)

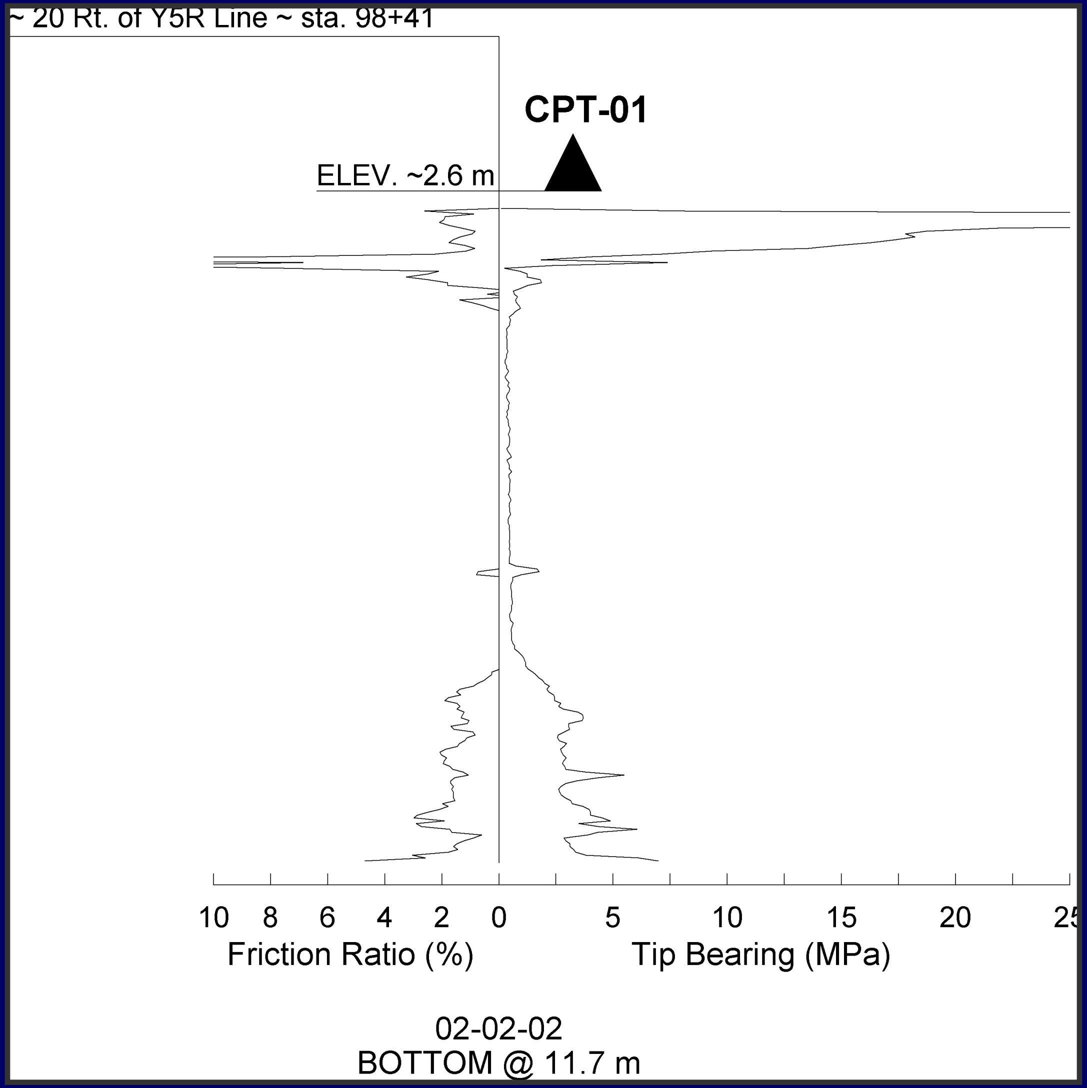


Graph produced using the program Seis Graph (seismic signal - time curve)



Additional methods of generating graphs of the CPT data

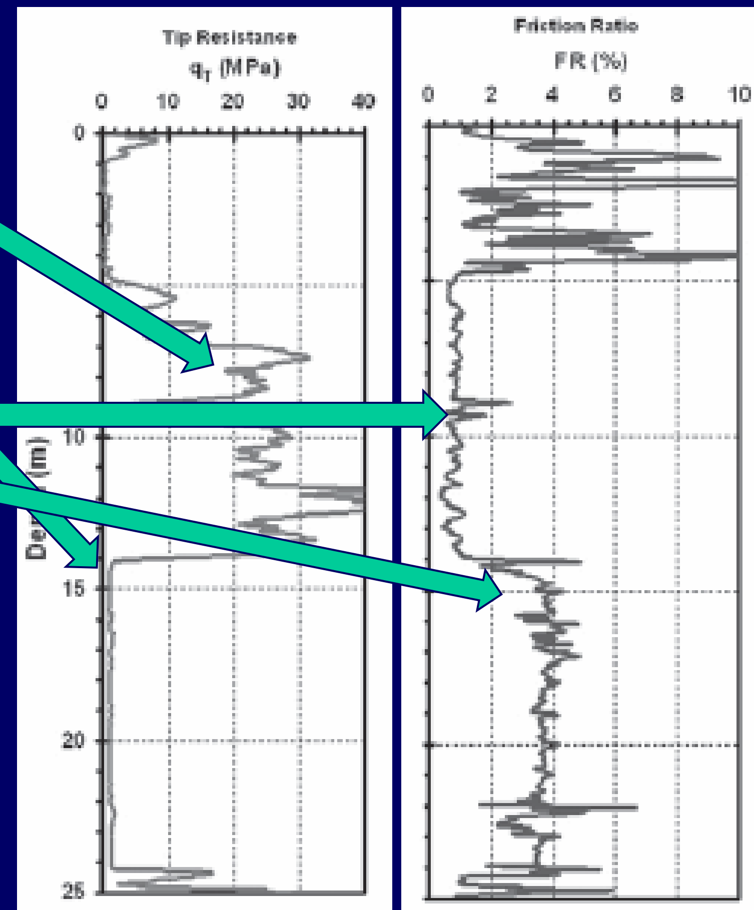
- Excel using the .csv file generated by Pro Dat
- gINT using the .gin file produced by Pro Dat
- Rapid CPT - $$$



Interpretation of the CPT geostratigraphy

Visual interpretation of geostratigraphy from the graphical presentation of CPT data

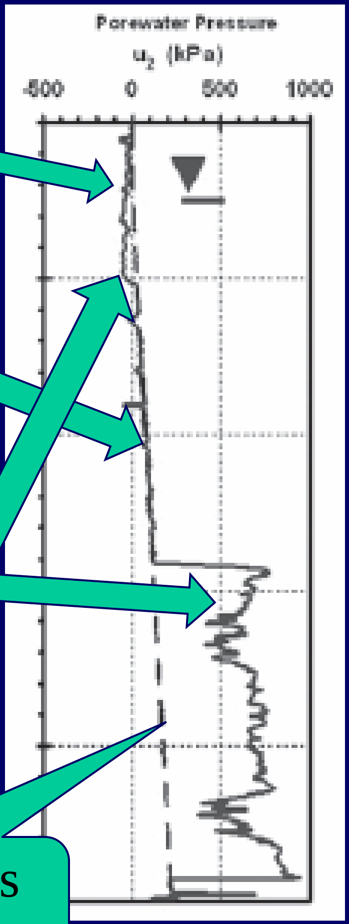
- Cone tip stresses, q_t
  - > 50 TSF in sands where drained conditions prevail
  - < 50 TSF in clays where the strength is controlled by an undrained response
- Friction ratio, R_f
  - < 1% in siliceous clean sands
  - >4% in non-sensitive clays and clayey silts
  - in soft, sensitive clays the friction ratio may approach 0%



Visual interpretation of geostratigraphy from the graphical presentation of CPT data

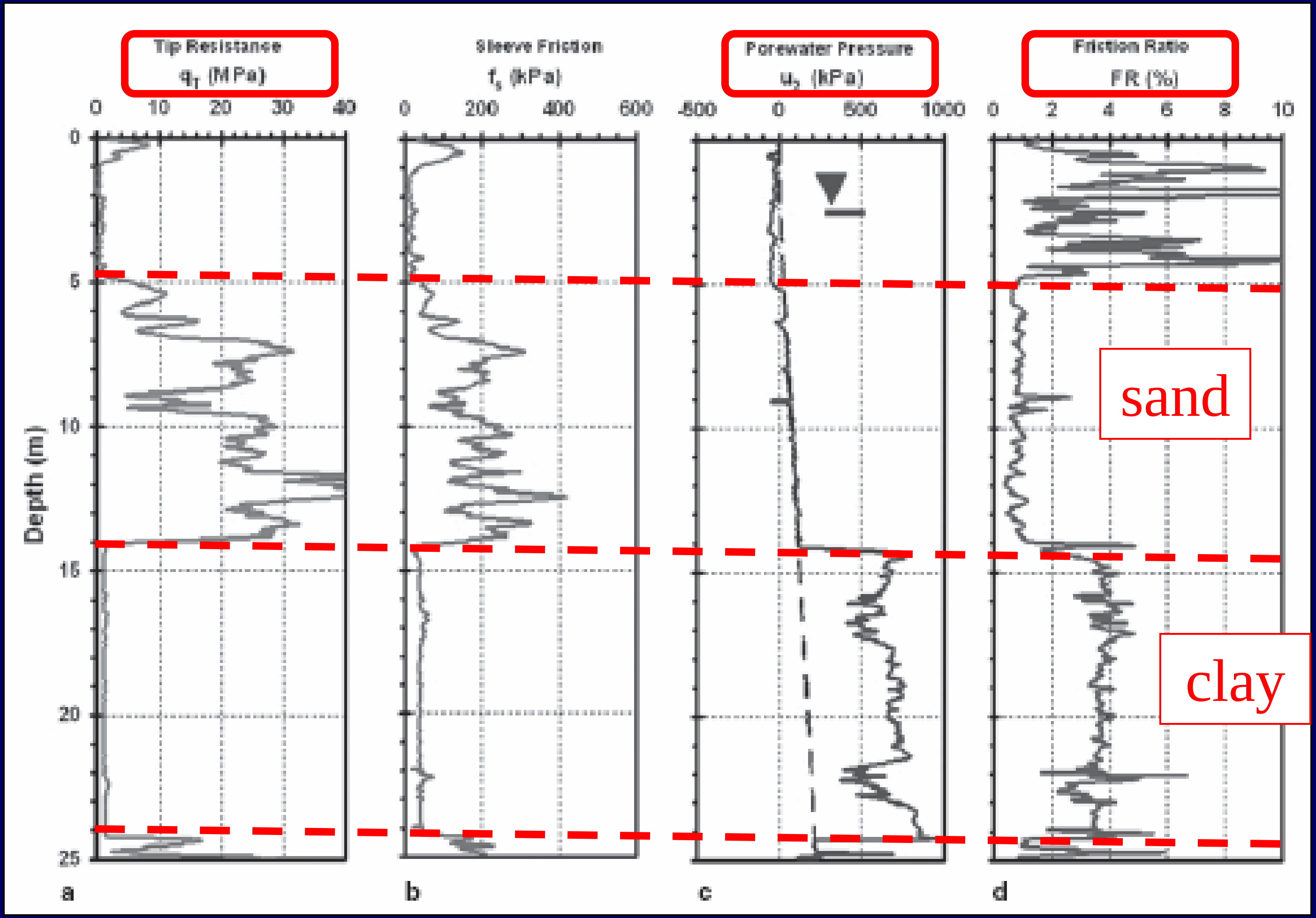
Porewater pressures, $u_t = u_2$

- above the water table (partially saturated soils) the pore pressure response may be greater or less than u_0
- in well-drained sands below the water table porewater pressures are close to static value ($u_t = u_0$)
- Intact clays below the water table exhibit porewater pressures above the static value ($u_t > u_0$), where u_2/u_0 increases with hardness
  - u_2/u_0 may be approximately 3 in soft intact clay
  - u_2/u_0 may be approximately 10 in stiff intact clay
  - u_2/u_0 may be 30 or more in hard intact clay
- Fissured clays below the water table exhibit porewater pressures close to zero or negative

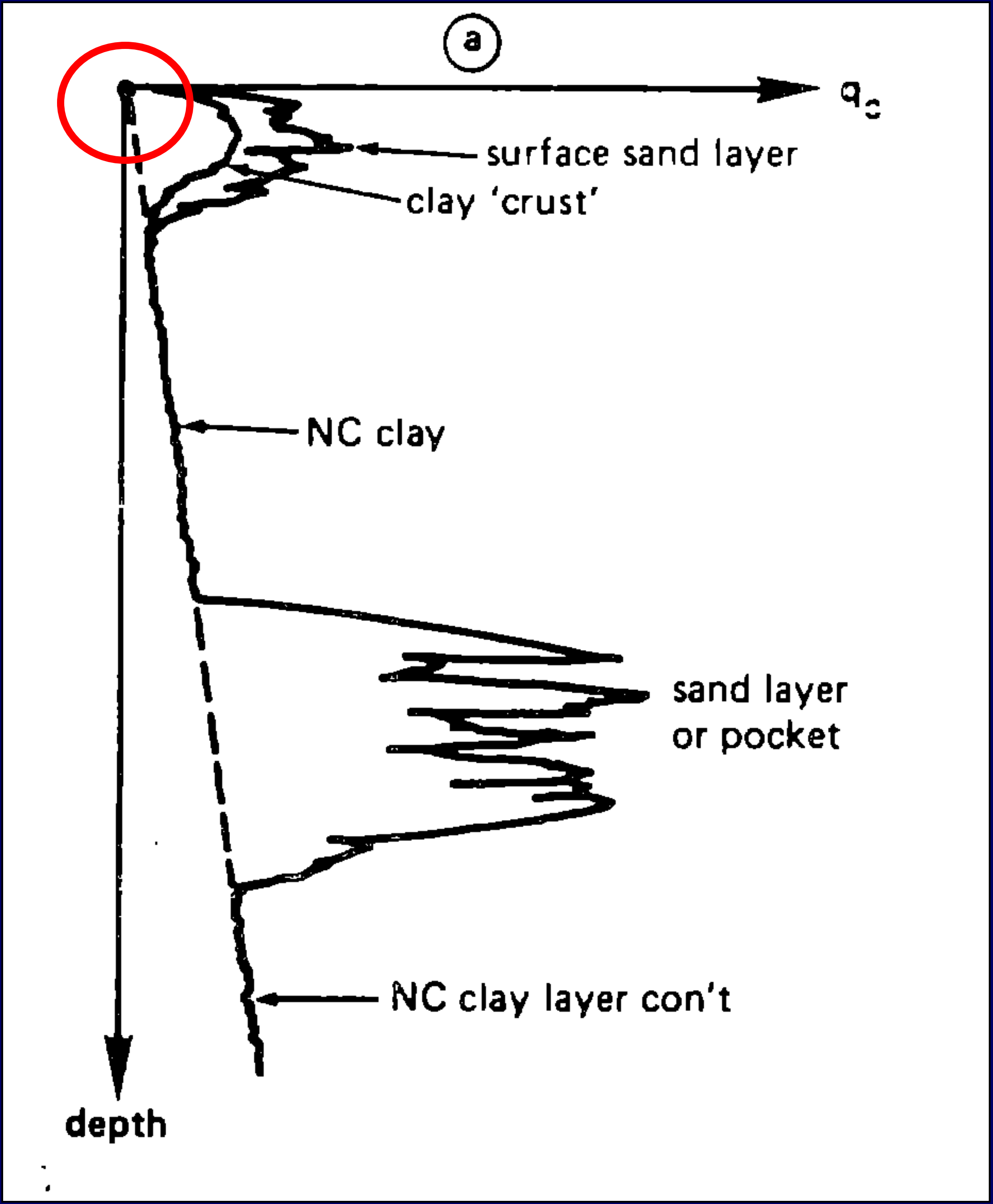


Dashed line is the u_0 profile

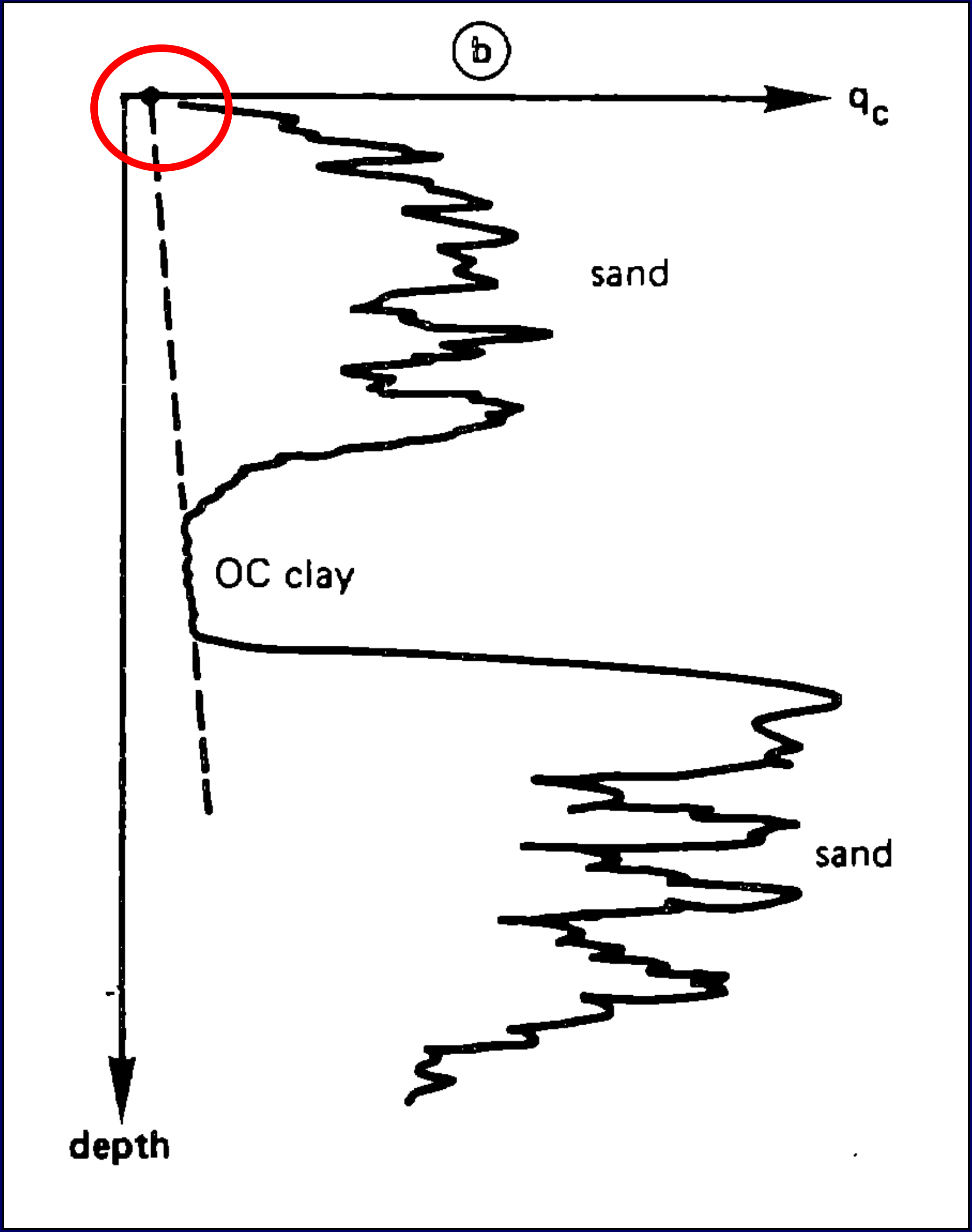
Visual interpretation of geostratigraphy from the graphical presentation of CPT data



The cone tip resistance of a normally consolidated clay increases linearly with depth, because the strength of the clay increases linearly with depth.



The cone tip resistance of an over-consolidated clay increases linearly with depth, where the strength of the clay increases linearly with depth.



Cone tip resistances increasing linearly with depth in soils where the soil strength is proportional to the depth.

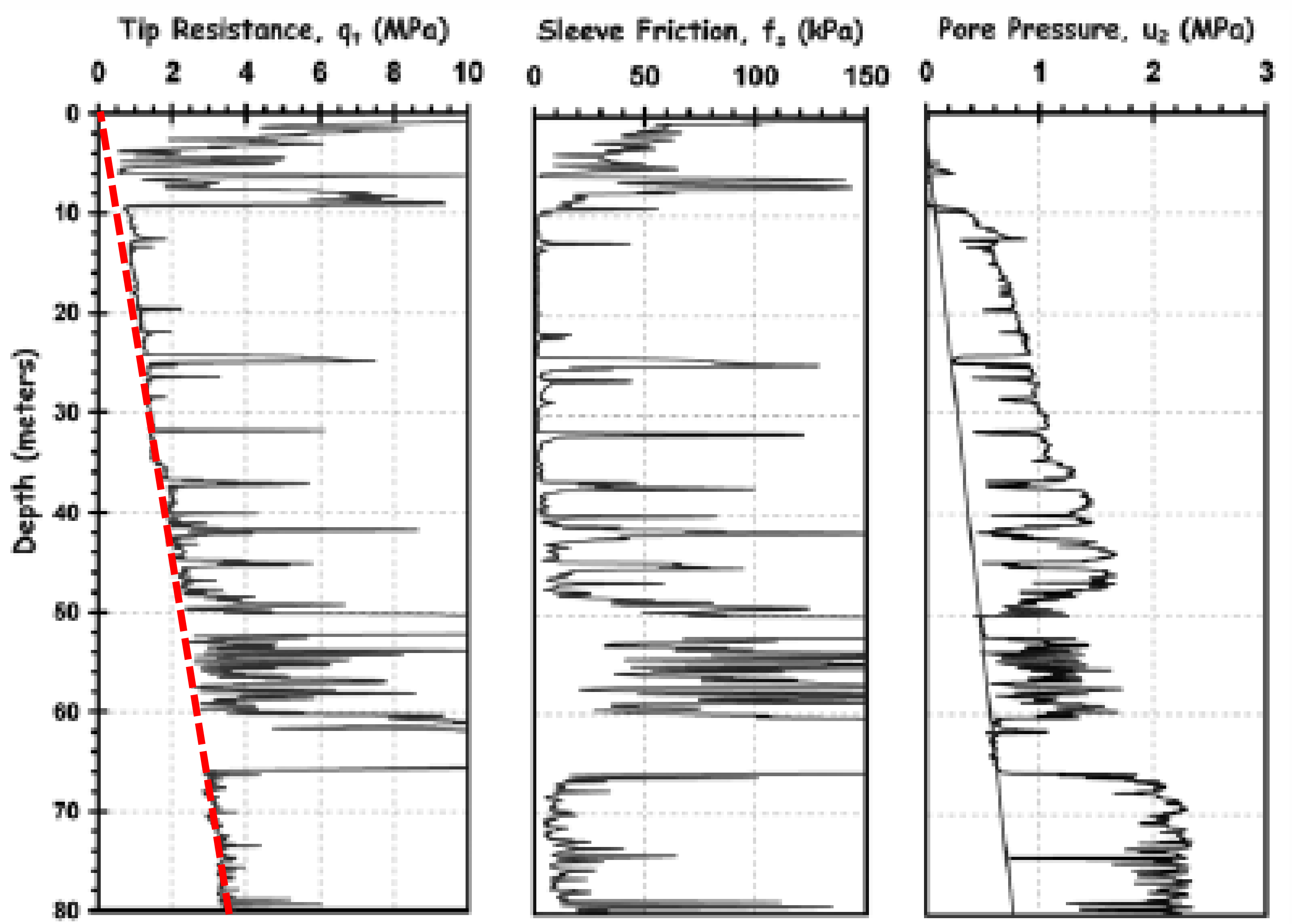
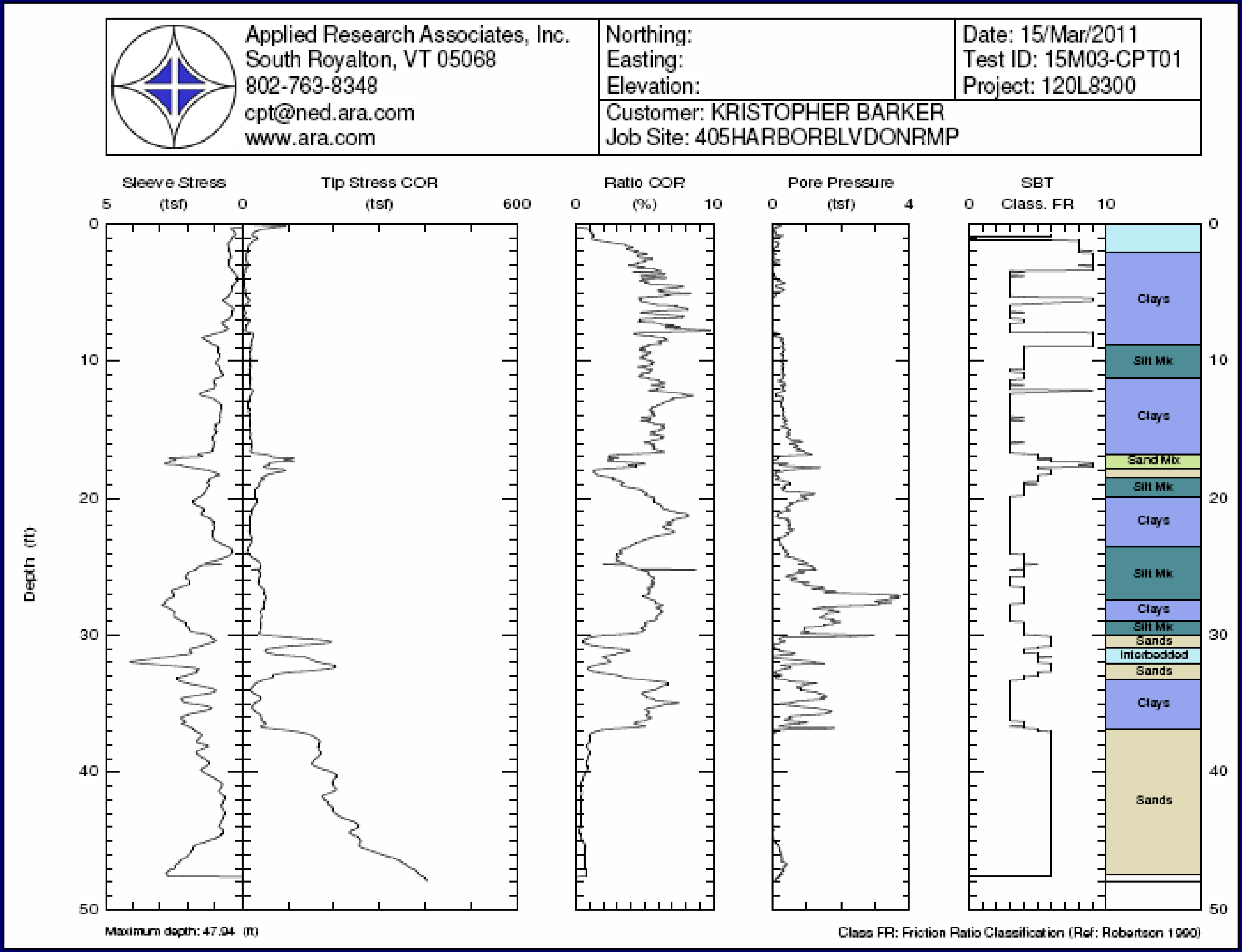
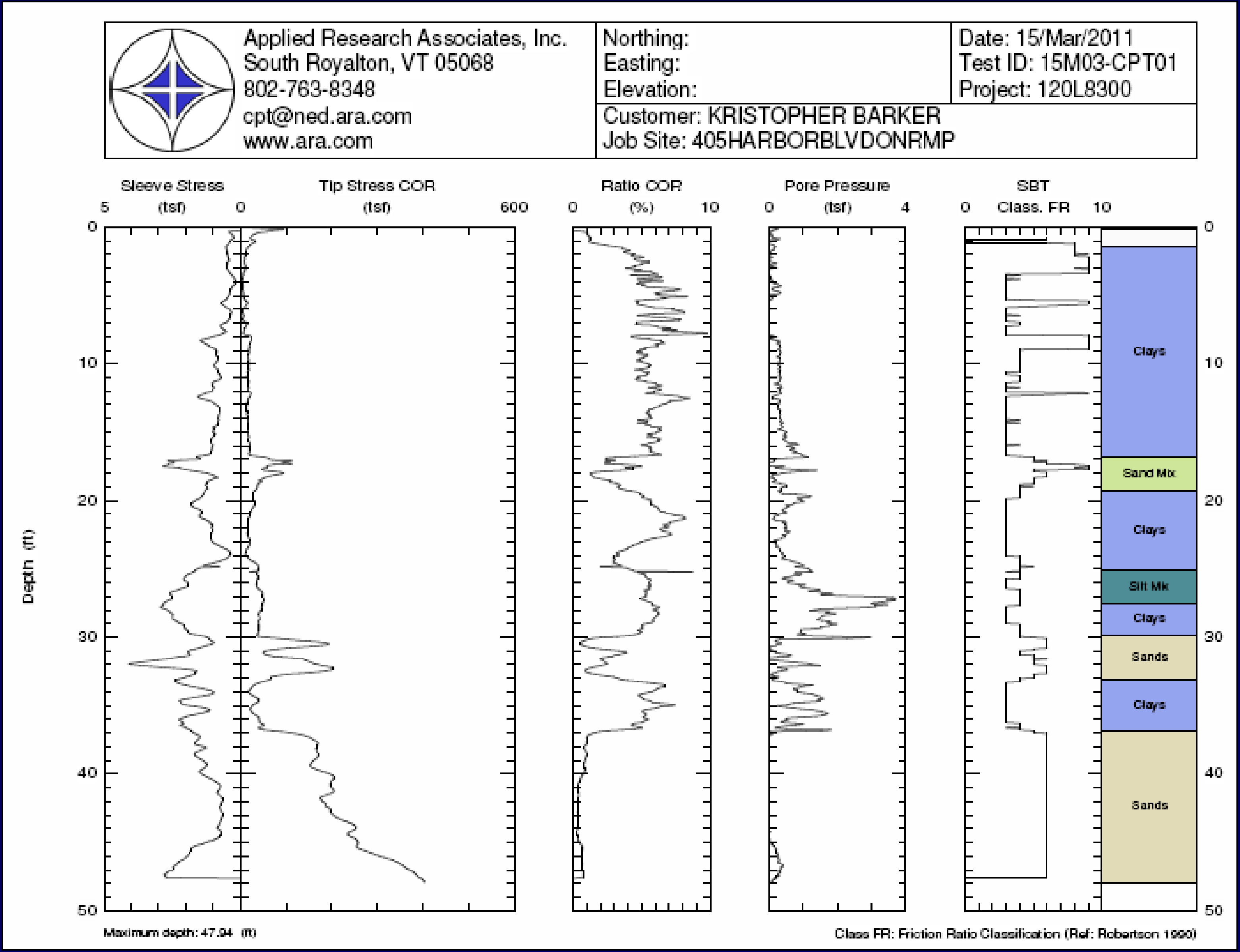


FIG. 4 Example Graph Presentation Results from a Conventional Piezocone Penetration Test

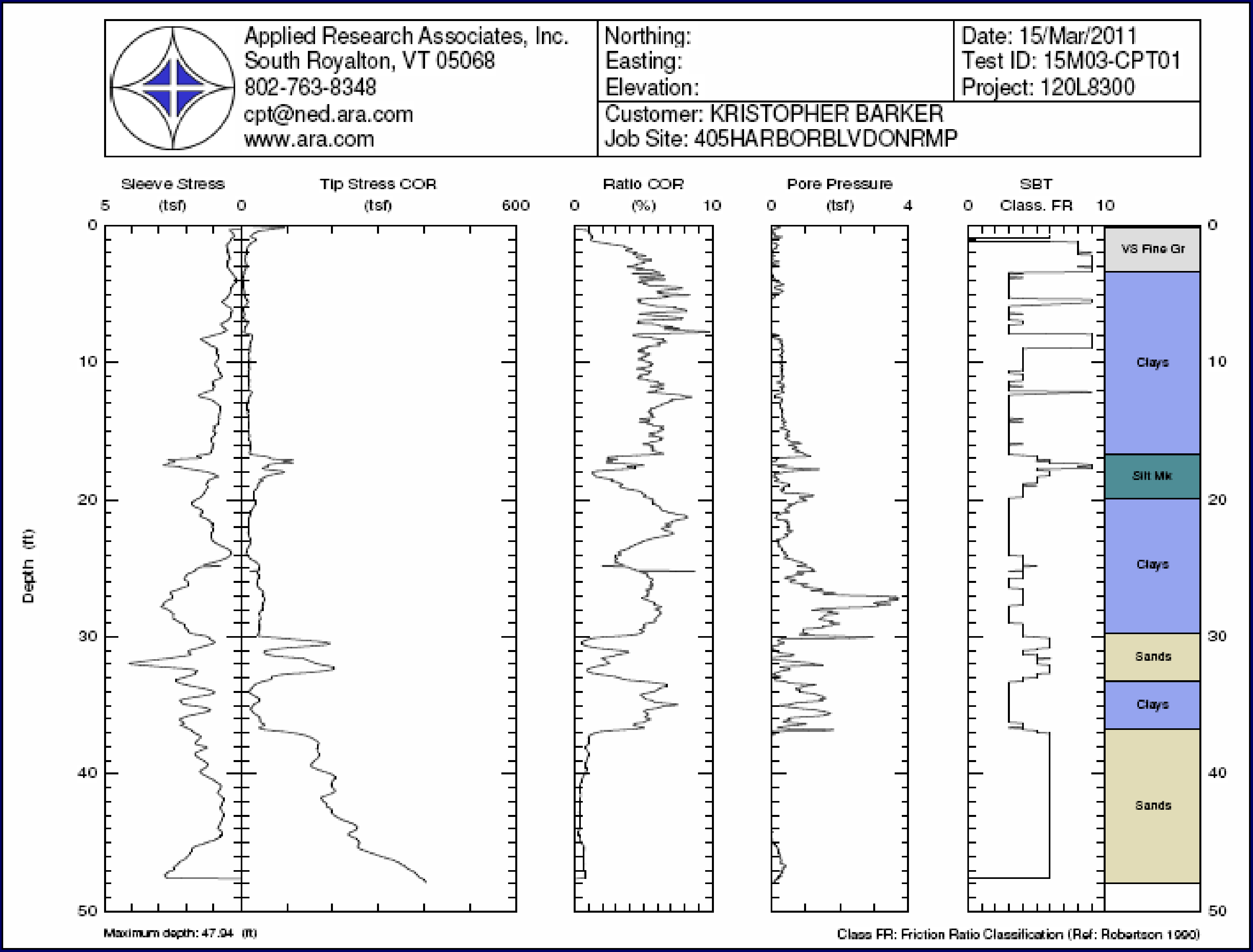
Graph produced using the program CPT Graph ("detail level" of 9 yields 15 strata using Robertson, 1990)



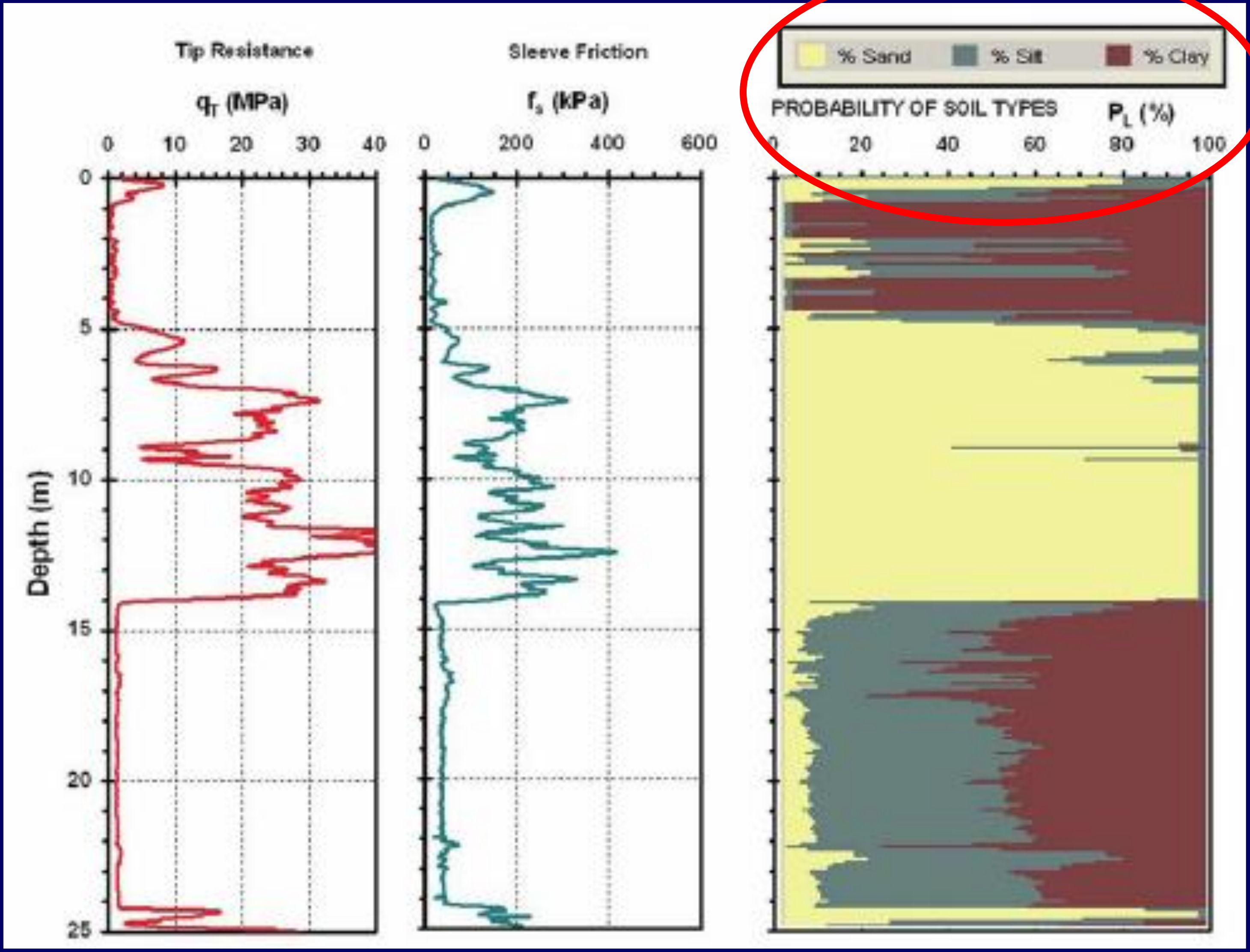
Graph produced using the program CPT Graph ("detail level" of 19 yields 8 strata)



Graph produced using the program CPT Graph ("detail level" of 50 yields 6 strata)



P-class or probabilistic method of assessing percentages of clay, silt, and sand
(“Soil CPT 4.0” by Zhang and Tumay, 1999)



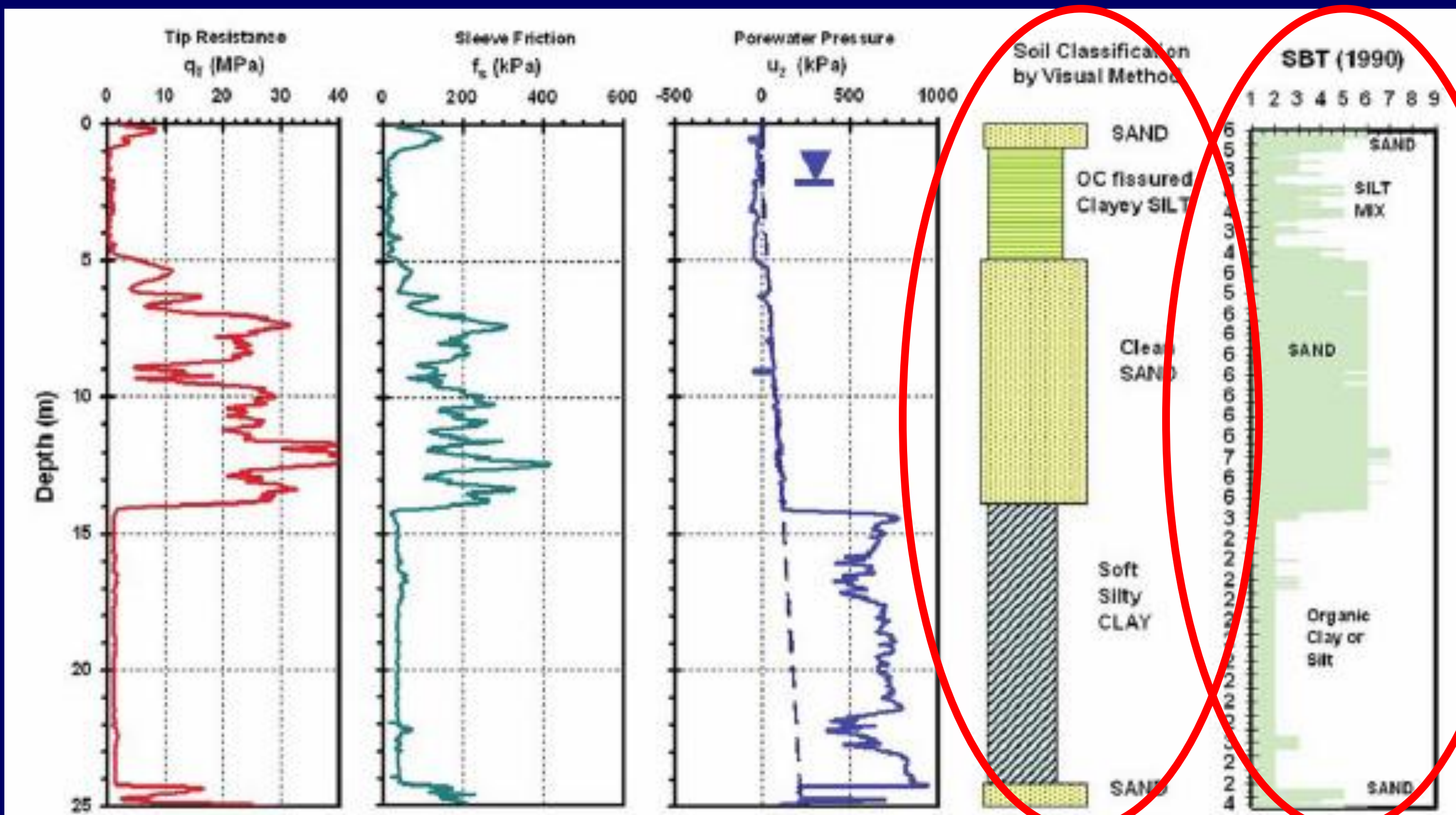
Soil behavior type evaluated with the soil classification index I_c (Jefferies and Davies, 1993)

$$*I_c = \sqrt{\{3 - \log[Q \cdot (1 - B_q)]\}^2 + [1.5 + 1.3 \cdot (\log F)]^2}$$

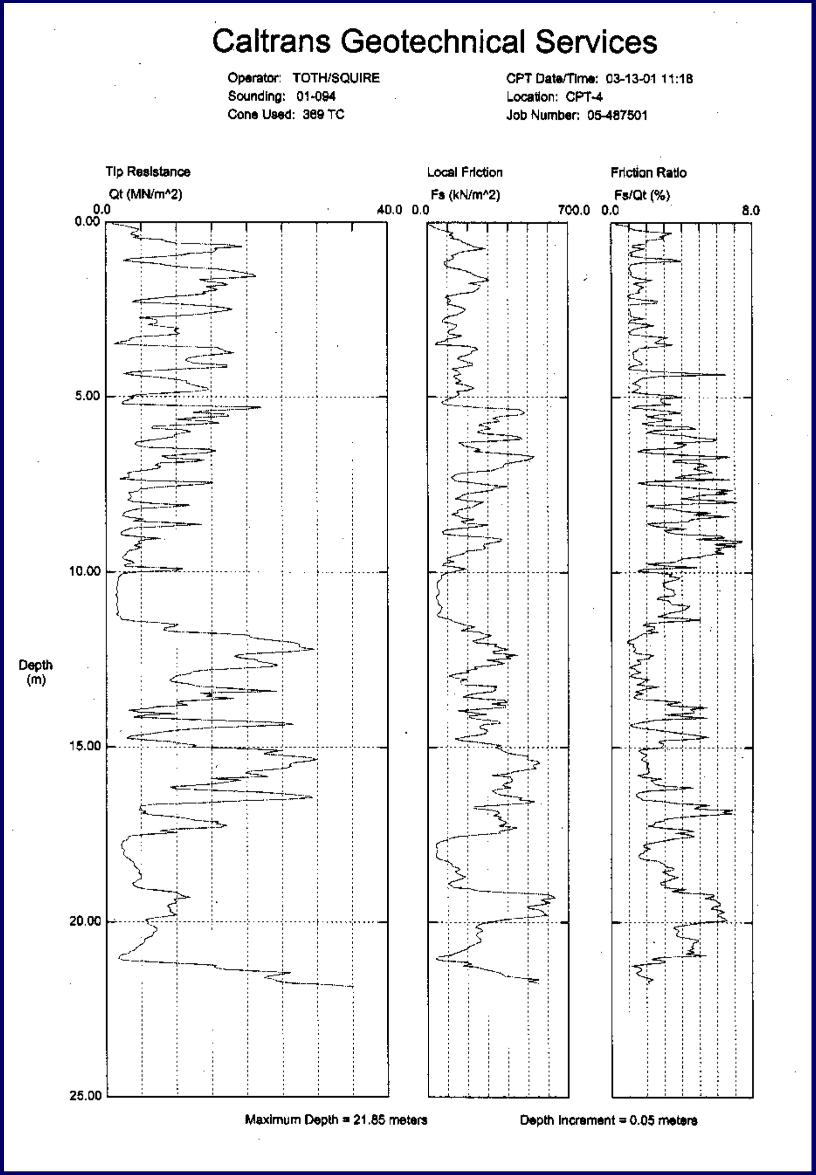
TABLE 2
SOIL BEHAVIOR TYPE OR ZONE NUMBER FROM CPT CLASSIFICATION INDEX, $*I_c$

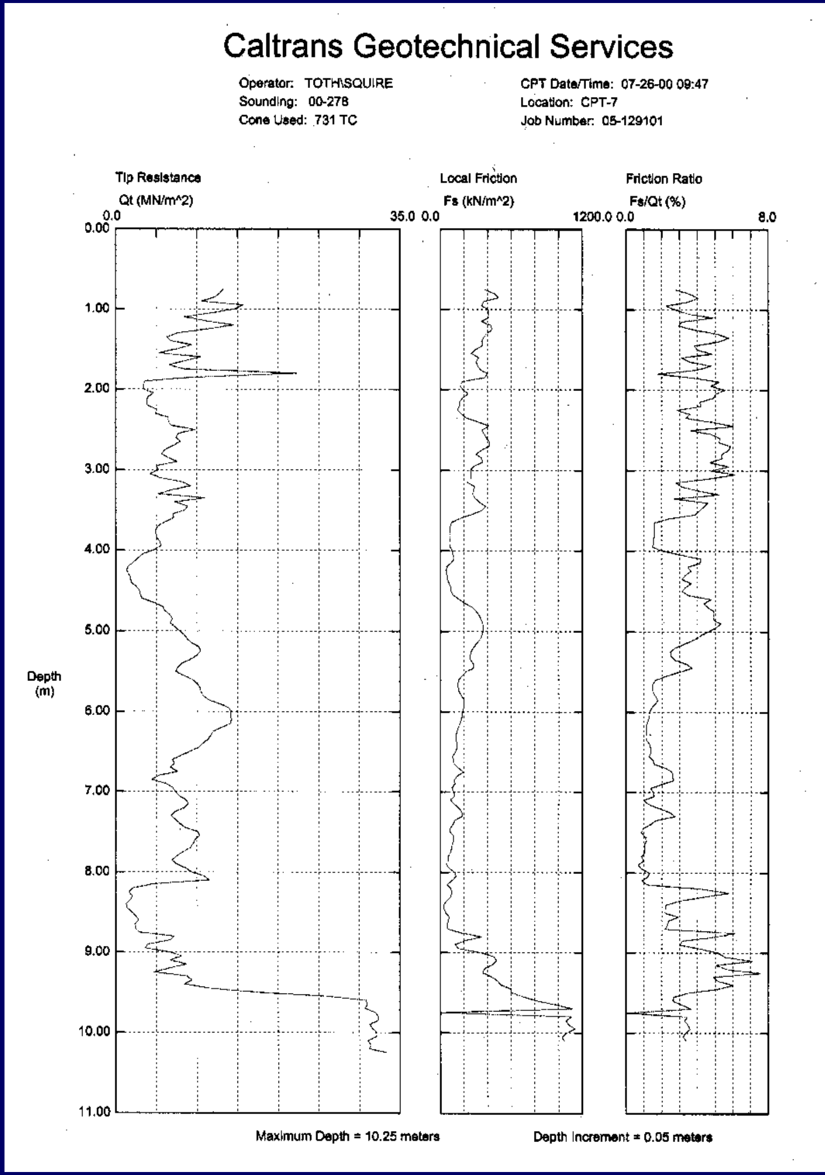
Soil Classification	Zone No.*	Range of CPT Index $*I_c$ Values
Organic Clay Soils	2	$I_c > 3.22$
Clays	3	$2.82 < I_c < 3.22$
Silt Mixtures	4	$2.54 < I_c < 2.82$
Sand Mixtures	5	$1.90 < I_c < 2.54$
Sands	6	$1.25 < I_c < 1.90$
Gravelly Sands	7	$I_c < 1.25$

After Jefferies and Davies (1993).
*Notes: Zone number per Robertson SBT (1990). Zone 1 is for soft sensitive soils having similar I_c values to Zones 2 or 3, as well as low friction $F < 1\%$.

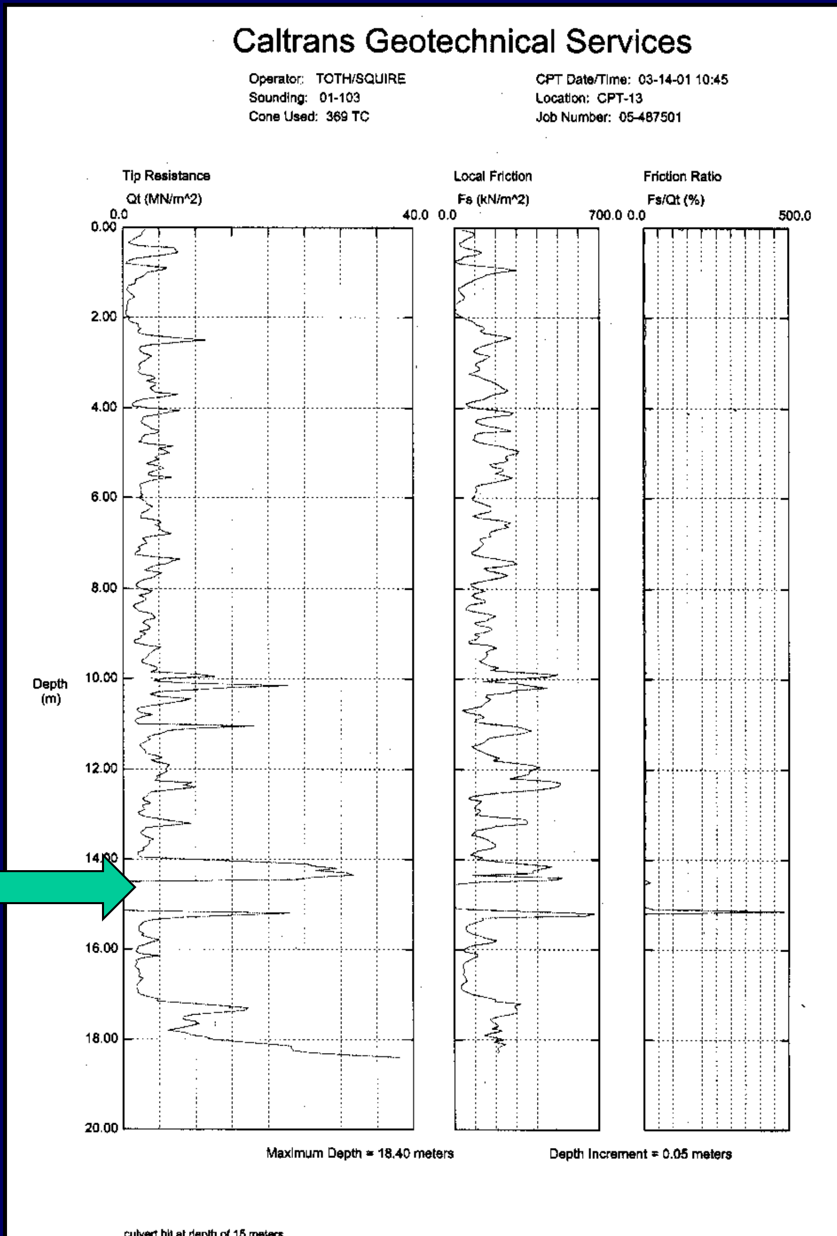


Comparison of the pattern of cone penetrometer data variations for fill and natural soil



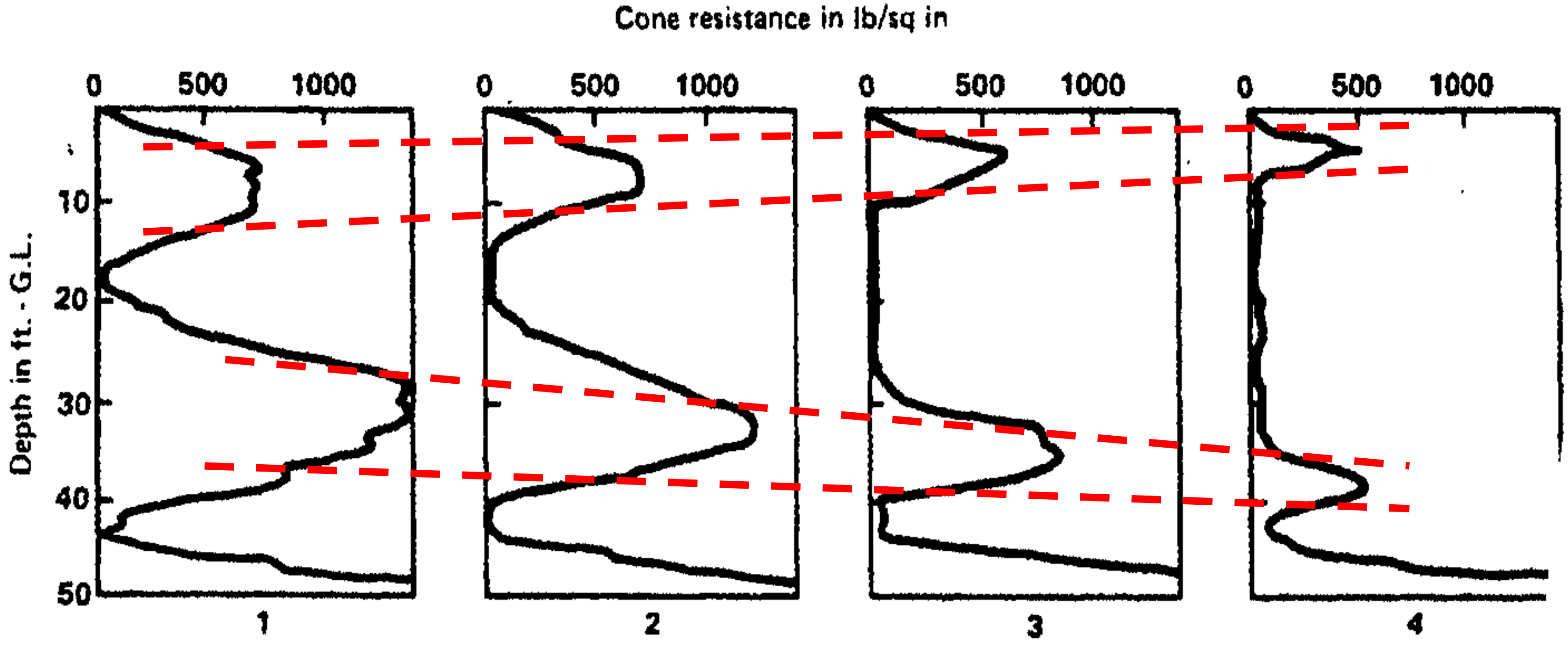


Voids can be located with the CPT



Continuity of strata can be determined with several CPT graphs displayed in cross section

In the first place one can determine quickly the trend of the layers in the vertical and horizontal directions.



Where is the boundary between soil layers?

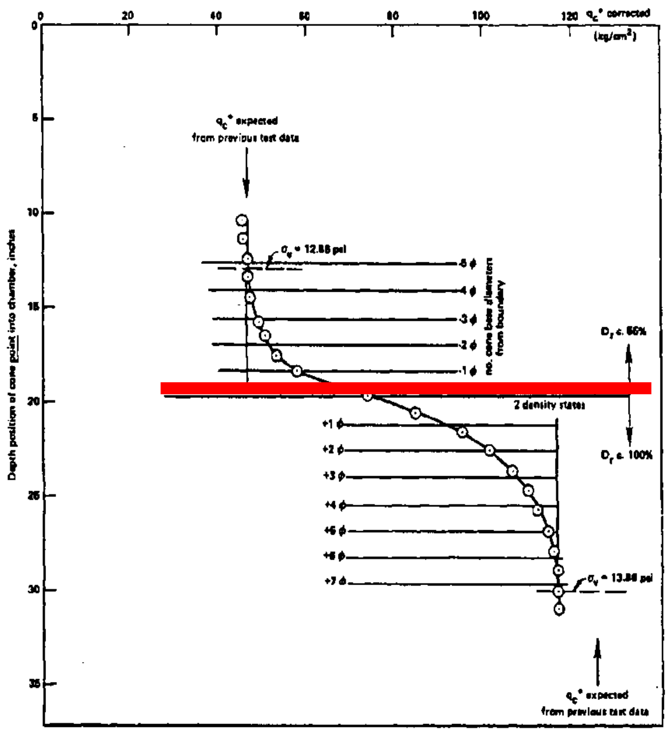


FIG. 6.4. Penetration of Fugro-Type Tip Through Loose to Dense Sand Boundary (q_c During Cone Advance Only) (from Schmertmann, 1978)

- When penetrating a stiff layer, the cone tip will begin to sense the <u>underlying softer layer</u> by a decreasing cone tip value at a distance of <u>1 foot</u> above the contact.
- When penetrating a soft layer, the cone tip will begin to sense the <u>underlying stiffer layer</u> by an increasing cone tip value at a distance of approximately <u>8 inches</u> above the contact.

How much penetration is required to reflect the true cone tip resistance of the penetrated soil layer?

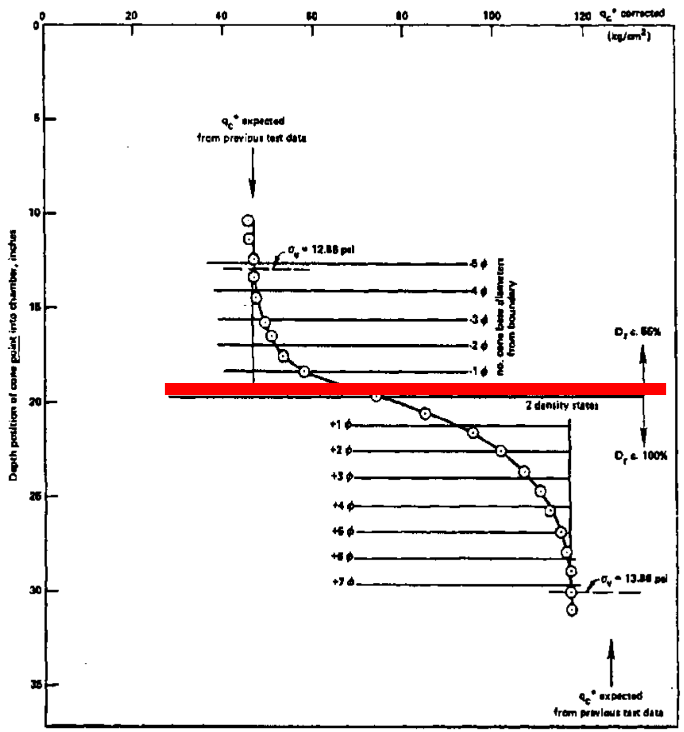


FIG. 6.4. Penetration of Fugro-Type Tip Through Loose to Dense Sand Boundary (q_c During Cone Advance Only) (from Schmertmann, 1978)

- When penetrating a stiff or strong layer (q_t > 7.5 TSF or s_u > 1000 psf) of uniform strength, the cone tip will not reflect the true cone tip resistance until the layer has been penetrated approximately 1 foot.
- When penetrating a soft or weak layer (q_t < 4 TSF or s_u < 500 psf) of uniform strength, the cone tip will not reflect the true cone tip resistance until the layer is penetrated approximately 8 inches.

Quantifying the effect of layer boundaries on the magnitude of the observed cone tip resistance.

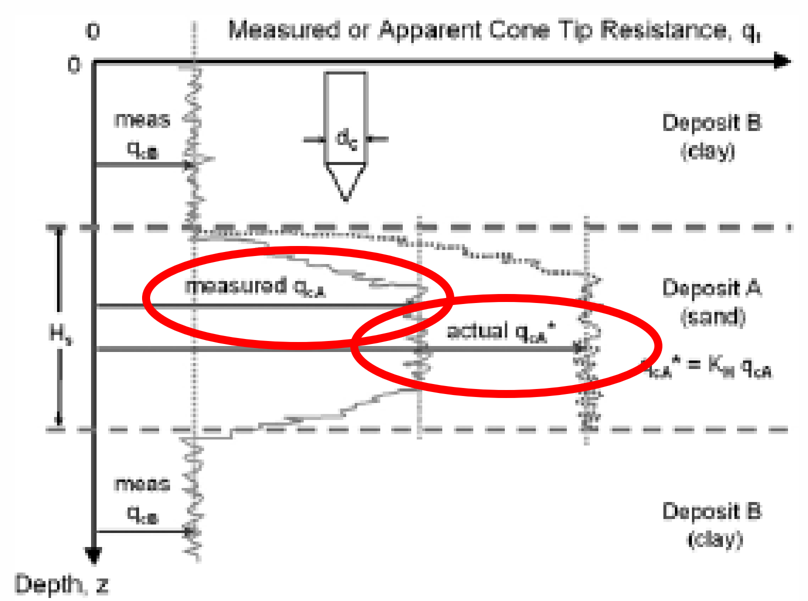


FIGURE 60 Situation of thin-layer effect on measured cone tip resistance (after Robertson and Wride 1998).

For a strong layer between substantially weaker layers, where the strong layer is less than approximately 4.5 feet thick, Ahmadi and Robertson (2005) recommend a conservative means of computing the actual tip resistance of the strong layer.

The corrected tip resistance of the strong soil layer can be conservatively calculated by:

$$\boxed{q_{tA}^* = q_{tA}\left(1 + 0.25\left(0.059\,(H_1/d_c) - 1.77\right)^2\right)}$$

q_{tA}^* = corrected tip resistance

q_{tA} = measured tip resistance

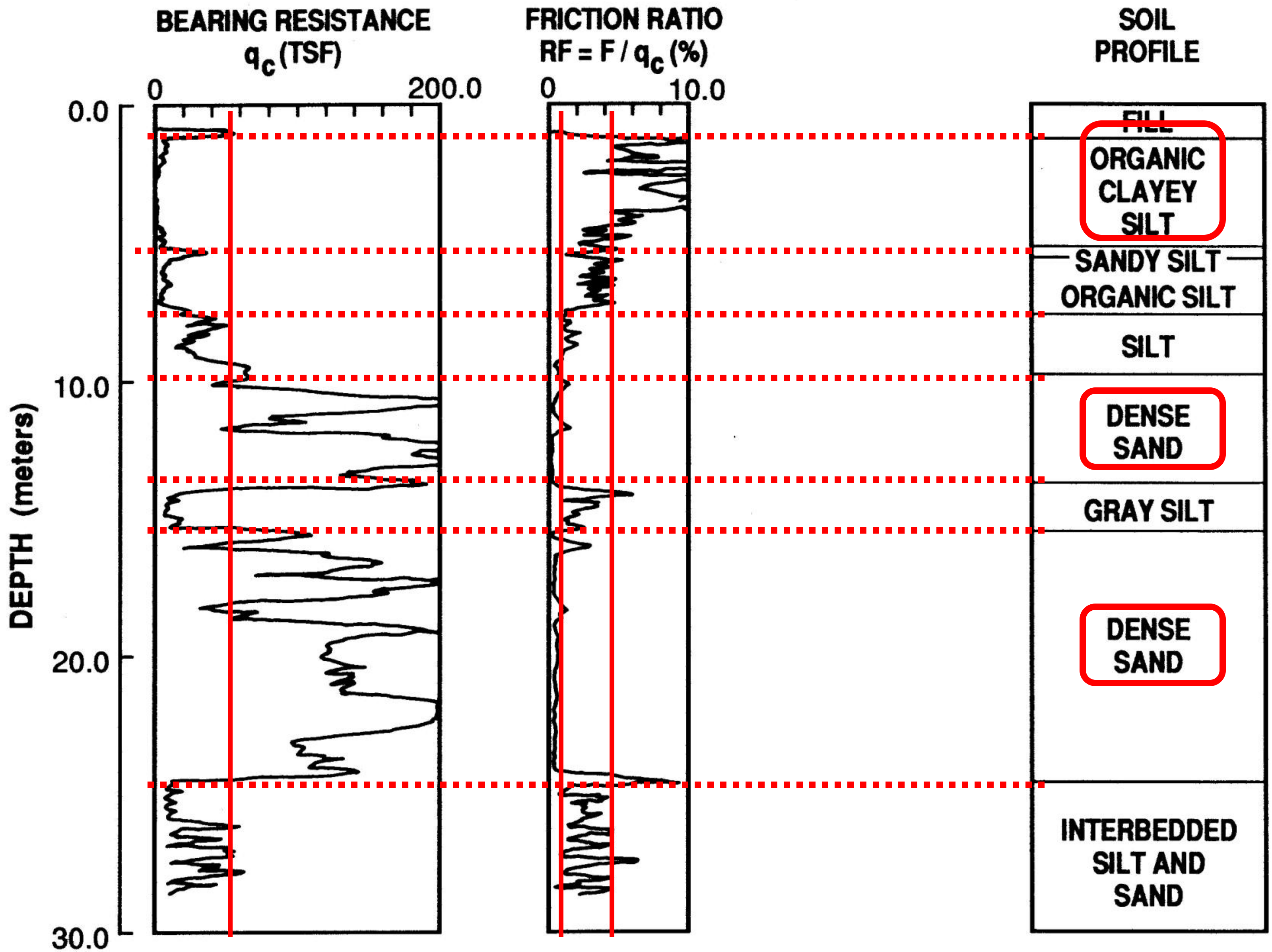
H_1 = thickness of the stronger soil layer

d_c = diameter of the cone tip = 1.75 inch

H_1	q_{tA}^*
24 inches	1.23 (q_{tA})
36 inches	1.08 (q_{tA})
52.5 inches	1.00 (q_{tA})

Important facts to remember when interpreting CPT data for SBT and stratigraphy

- Graphic depth plots of q_t, R_f, and u_t are excellent tools for determination of geostratigraphy.
- The location of the stratigraphic contacts should be selected using a consistent methodology.
- The cone tip readings may not be accurate for thin soil layers.
- If necessary, data can be processed to determine soil behavior types to very fine detail.
- Depth to groundwater is required for interpreting the penetration porewater pressures.
- The measured total piezometric pressure is effected by many factors, and its interpretation can be complicated by the degree of saturation, density and presence of fissures.



PIEZOMETER CONE PROFILE

Exercise 2

Determining geostratigraphy
with CPT data